

## Vacuum Variable-Temperature Blackbody VTBB100

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Published online: 16 January 2008  
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**Abstract** The present state-of-the-art of precision radiometry based on the vacuum variable-low-temperature blackbody source VTBB100 developed for the low-background calibration facility at PTB is analyzed. This article describes the vacuum variable-low-temperature blackbody (VTBB) constructed to serve as a highly stable reference source for the calibration of blackbody sources in the temperature range from 100 K to 450 K under medium-vacuum conditions ( $10^{-3}$  Pa) in a medium-background environment (liquid-nitrogen-cooled shroud). The general concept and the design of the VTBB100 are given. The numerical investigation of the effective emissivity of the VTBB100 is performed. A description of the temperature control and measurement system of the VTBB100 is presented. Cooling of the VTBB100 is by liquid nitrogen. Heating of the VTBB100 is by a two-stage temperature control scheme. A thermal model of the radiator was developed. As a result of the analysis, it was shown that the system achieves an instability of the blackbody temperature of less than 20 mK. The characteristics of the blackbody operation—now at PTB—are described.

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

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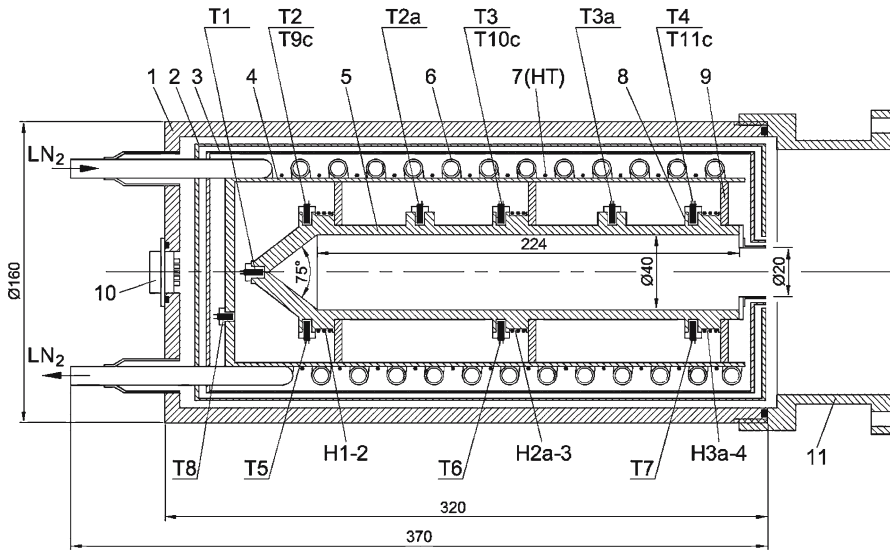
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## 1 Introduction

Measurements of the characteristics of various radiation sources in the infrared spectral range are of great importance for both science and technology. In order to solve this problem, cryo-vacuum systems including low-temperature radiators and infrared radiometers at the level of both the reference and working measuring instruments and standards are being created at various metrological institutes [1–3]. The vacuum variable-low-temperature blackbody (VTBB100) was developed for the low-background calibration facility at PTB [4]. The VTBB100 was constructed as a highly stable reference source for the calibration of blackbody sources in the temperature range from 100 K up to 450 K under medium-vacuum conditions ( $10^{-3}$  Pa) in a medium-background environment (liquid-nitrogen-cooled cryo-shroud).

## 2 Principle of Operation of the VTBB100

The VTBB100 is a deep radiation cavity with a cooled aperture. The aperture is cooled by a heat-link to a reservoir containing liquid nitrogen in the vacuum chamber in which the blackbody is installed. The cavity has a cylindrical form with a conical bottom. The main parts of the VTBB are the radiation cavity, a liquid nitrogen cryo-shroud, radiation screens, ring heat sinks between the cavity and cryo-shroud, and two systems (coarse and fine) for the VTBB100 temperature stabilization. All the elements of the VTBB100 are contained within a vacuum housing. The vacuum enclosure allows operation of the blackbody VTBB100 to temperatures as low as 100 K. Coarse control of the VTBB100 temperature within 10–15°C of the working temperature is performed with cooling by the liquid nitrogen and heating by the electrical heaters that are fixed around the cryo-shroud. The liquid nitrogen cryo-shroud is surrounded by a system of radiation shields. The temperatures of the cryo-shroud and screens are measured by platinum resistance thermometers. The temperature of the cryo-shroud is established about 10–15°C below the operational temperature of the VTBB100. The required homogeneity of temperature along the radiator cavity, which is made of oxygen-free copper, is determined by the design of the cavity (most significantly by the wall thickness, which is 5 mm), and is adjusted by a precision electronic system designed for radiator cavity temperature stabilization. The calculations carried out have shown that it is possible to achieve a temperature gradient along the cavity of not more than 20 mK with a wall thickness of the radiator cavity of 5 mm and the use of a three-zone system for radiator cavity temperature stabilization. A schematic drawing of the Blackbody VTBB100 is presented in Fig. 1. Measurement and control of the three-zone system for radiator cavity temperature stabilization is performed by platinum resistance thermometers T2, T5, T9c, T3, T6, T10c, T4, T7, and T11c in conjunction with heaters H1-2, H2a-3, and H3a-4 that are structurally arranged in three ring-type crossbars (8) on the external surface of the radiator cavity (6). The ring-type crossbars (8) are connected through heat-links (9) to the cryo-shroud (4). The platinum resistance thermometers and electrical heaters are components of a precision system for radiator cavity temperature stabilization that maintains a gradient of temperature

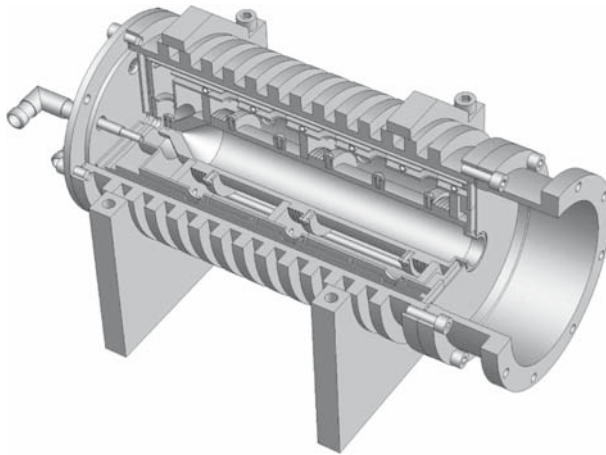


**Fig. 1** Schematic drawing of the Blackbody VTBB100: 1—Body of the VTBB100; 2—Second Radiation Screen; 3—First Radiation Screen; 4—Cryo-shroud; 5—Cavity; 6—Cryo-shroud heat-exchanger; 7—Cryo-shroud Heater (HT); 8—Ring type crossbar on the cavity; 9—Heat-link; 10—Electrical Connector; 11—Flange for low-background facility connection; H1-2, H2a-3, H3a-4—Heaters of the VTBB100 first, second, and third zones, accordingly

along the cavity within 10 mK or less over the whole operating temperature range from 100 K to 450 K.

### 3 Design Features of the VTBB100

Blackbody VTBB100 (Fig. 1) consists of the following units: cavity (5) with three heat-links (9), three cavity heaters H1-2, H2a-3, and H3a-4 of the VTBB100 first, second, and third zones, respectively, 13 Pt resistance thermometers, cryo-shroud (4) with heat-exchanger (6), heater (7), and radiation screens (2) and (3). The VTBB100 cavity (5) is 40 mm in diameter and 250.6 mm in length and made of oxygen-free copper. The cavity shape is cylindrical, with a conical bottom, and has an aperture diameter of 22 mm. The inner walls of the cavity are covered by a black Aeroglaze Z306 paint. The external walls of the cavity are polished to reduce the influence of radiation exchange. The external surface of the cavity has three thicker portions on which ring heat-links (9) and cavity heaters are fixed. The surface temperature of the cavity is monitored with precision platinum resistance thermometers (T1, T2, T2a, T3, T3a, T4, T5, T6, and T7) with a certified stability of  $\leq 50$  mK per year and a calibration traceable to ITS-90 with an uncertainty of  $\leq 30$  mK ( $k = 2$ ). The fast-response thermometers (T8, T9c, T10c, and T11c) are used to control the cavity temperature. Six Pt resistance thermometers T1, T2, T2a, T3, T3a, and T4 are used for precision temperature measurements along the cavity; the Pt resistance thermometers T5, T6, and T7 are used to measure the temperatures of the first, second, and third zones, respectively (these



**Fig. 2** Structure of the blackbody VTBB100 with cross section

data are used for the precision temperature controller), T8 is used for coarse control of the VTBB100 temperature with the help of the cryo-shroud; T9c, T10c, and T11c are used for fine control of the VTBB100 first-, second-, and third-zone temperatures, respectively.

The cavity is placed inside the cryo-shroud (4). The cryo-shroud is heated or cooled by the heat exchanger (6) through which liquid nitrogen flows. An electrical heater (7) is mounted on the cryo-shroud. The inner walls of the cryo-shroud are polished to reduce the influence of radiative exchange with the blackbody. The cryo-shroud (4) is surrounded by radiation screens (2) and (3). A sealed electrical connector (10) and two nipples for liquid nitrogen are fixed on the back surface of the outer body (1).

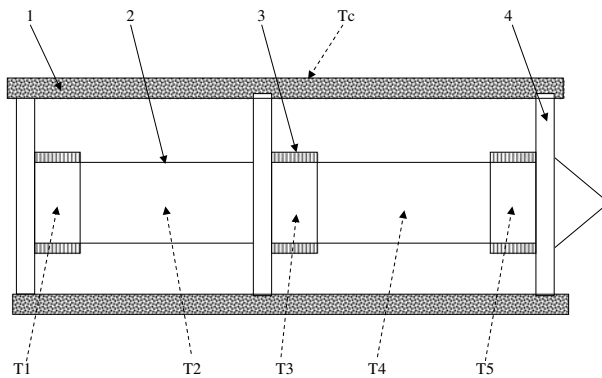
Cooling of the VTBB100 is achieved by liquid nitrogen. The flow of liquid nitrogen goes through the tube which is fixed around the cryo-shroud. There are two output holes at the end of this cooling tube. The first output hole on the bottom of the VTBB100 cavity has a small diameter and the second output hole has a larger diameter. The second output hole is closed by the valve V1. A small flow of liquid nitrogen goes through the tube around the cryo-shroud when valve V1 is closed, and a large flow goes through the tube around the cryo-shroud when the valve V1 is open. A large flow is used when it is necessary to decrease the temperature of the VTBB100 cavity. A small flow of liquid nitrogen is used in the temperature range from  $-173^{\circ}\text{C}$  to  $+40^{\circ}\text{C}$  when stabilizing the temperature of the VTBB100. Stabilization of the VTBB100 temperature in the temperature range from  $+40^{\circ}\text{C}$  up to  $+177^{\circ}\text{C}$  is performed without liquid nitrogen. The structure of the Blackbody VTBB100 in cross section is presented in Fig. 2. The specifications of the VTBB100 (derived from measurement) are presented in Table 1.

#### 4 Mathematical Model of the VTBB100 Temperature Control System

Estimation of the stability of the coupled loops for automatic control of the blackbody temperature was required to assist with the design of the vacuum variable-low-

**Table 1** Specifications of VTBB100

Range of radiation temperature (K (°C))	100–450 (–173 to 177)
Instability of PRT-temperature and radiation temperature (mK)	<20 (after settling time)
Normal effective emissivity	>0.9997
Cavity diameter (mm)	40
Cavity length (mm)	250
Outer aperture diameter (mm)	20
Shape of cavity bottom	75° outer cone
Overall dimensions of VTBB100 (diameter × length) (mm)	200 × 450
Temperature differences along the cavity, measured with the six PRTs (mK)	<20 (after settling time)
Settling time (300 K up to 450 K) (min)	<30
Settling time (300 K down to 100 K) (min)	<60
Ambient temperature range for operation (°C)	15–30
Temperature of the outer wall of the VTBB100 (°C)	15–40
Application	In vacuum chamber
Mass of VTBB100 (kg)	<15



**Fig. 3** Simplified design of the VTBB100 for mathematical simulation of the blackbody temperature control. The Pt resistance thermometers have different labels in this drawing compared to the schematic drawing of the Blackbody VTBB100: 1—cryo-shroud for coarse temperature control of the blackbody; 2—the blackbody cavity radiator; 3—zone of a thickening of the radiator cavity wall to locate an electrical heater for blackbody fine temperature control; 4—Ring heat-link between the cryo-shroud and the radiator;  $T_c$ —a point for the cryo-shroud temperature measurement;  $T_1 - T_5$ —points for temperature measurements in different zones of the radiator

temperature blackbody VTBB100. The analysis of the stability of the multi-loop control system (MCS) was carried out with the help of a package of mathematical calculations (SIMULINK) within the framework of the program MATLAB. The MCS is based on a thermophysical model of the VTBB100 that includes all elements of the blackbody temperature stabilization system. The simplified circuit of the VTBB100 for mathematical simulation of the blackbody temperature control is shown in Fig. 3.

The thermophysical model (TPhM) of the radiator was based on the equations of thermal balance for five elements of the radiator: three ring zones where the heating

windings are located (with average temperatures  $T_1$ ,  $T_3$ , and  $T_5$ ) and two cylindrical zones connecting the three ring zones (with average temperatures  $T_2$  and  $T_4$ ):

$$C_1 \frac{dT_1}{dt} = P_1 + \lambda_1(T_2 - T_1) + \lambda_2(T_C - T_1), \quad (1a)$$

$$C_2 \frac{dT_2}{dt} = \lambda_1(T_3 + T_1 - 2T_2), \quad (1b)$$

$$C_1 \frac{dT_3}{dt} = P_2 + \lambda_1(T_2 - T_3) + \lambda_1(T_4 - T_3) + \lambda_2(T_C - T_3), \quad (1c)$$

$$C_2 \frac{dT_4}{dt} = \lambda_1(T_3 + T_5 - 2T_4), \quad (1d)$$

$$C_3 \frac{dT_5}{dt} = P_3 + \lambda_1(T_4 - T_5) + \lambda_2(T_C - T_5), \quad (1e)$$

where  $C_i$ s are the thermal capacities of parts of the radiator ( $J \cdot K^{-1}$ ),  $P_i$ s are the heater powers (W),  $\lambda_i$ s are the thermal conductivities between the various parts of the radiator and between the radiator and the cryo-shroud ( $W \cdot K^{-1}$ ), and  $T_C$  is the temperature of the cryo-shroud (K).

The transition from a thermophysical model to the model of a multi-loop control system (MCS) occurs at the stage where the power for each heater is defined by the difference between the current temperature  $T_i$  and the setting temperature  $T_{SET}$ . The heating power for each zone is defined by a sequence of transformations dependent on a difference of temperatures:

$$P_i = F_{TIn}\{F_{CA}[F_{PID}(T_{SET} - T_i)]\}, \quad (2)$$

where  $F_{PID}(T_{SET} - T_i)$  is a function of the temperature controller, including the sum of the proportional, integral, and differential components,  $F_{CA}(x) = K(\text{abs}(x) + x)^2$  is the function describing the output of the current amplifiers which transform the output voltage of the controller to the power of the heating winding, and  $F_{TIn}(x)$  is the function that simulates the thermal inertia of a heater winding.

For computer simulation with the help of the graphical simulation software (SIMULINK), the above-mentioned system of equations is reduced to

$$T_1 = -\tau_1 \frac{dT_1}{dt} + \frac{P_1}{\lambda_1 + \lambda_2} + k_1 T_2 + k_2 T_C, \quad (3a)$$

$$T_2 = -\tau_2 \frac{dT_2}{dt} + \frac{T_3 + T_1}{2}, \quad (3b)$$

$$T_3 = -\tau_3 \frac{dT_3}{dt} + \frac{P_2}{2\lambda_1 + \lambda_2} + k_3 T_2 + k_3 T_4 + k_4 T_C, \quad (3c)$$

$$T_4 = -\tau_2 \frac{dT_4}{dt} + \frac{T_3 + T_5}{2}, \quad (3d)$$

$$T_5 = -\tau_4 \frac{dT_5}{dt} + \frac{P_3}{\lambda_1 + \lambda_2} + k_1 T_4 + k_2 T_C, \quad (3e)$$

where  $\tau_1 - \tau_4$  are time constants,  $k_1 - k_4$  are dimensionless factors connected by the following:

$$k_2 = (1 - k_1), \quad k_3 = k_1/(1 + k_1), \quad k_4 = (1 - k_1)/(1 + k_1) \quad (4)$$

In this way, the stability of the MCS was defined (other than by time parameters) by only one parameter, which is equal to the ratio of the heat conductivity between the ring zones and the heat conductivity between a ring zone and the cryo-shroud.

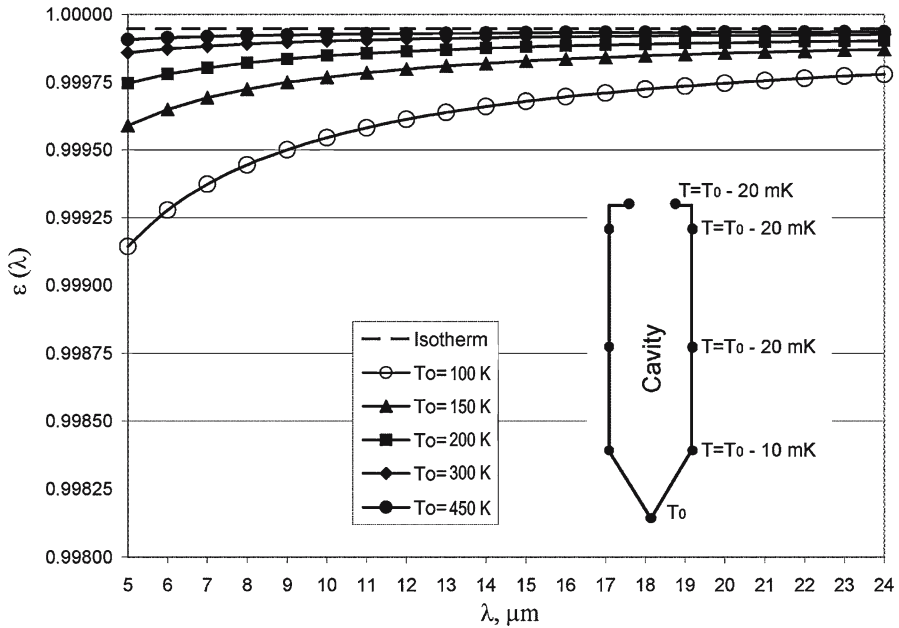
As a result, the response to a transient is practically identical for all three loops of the temperature control and the settling time for all control loops is maintained when the coefficients for the heat-links between the loops correspond to the actual thermophysical parameters of the radiator. The settling time of temperature  $T_2$  increases with an increase in the conductivity of the heat-link, but the system does not lose stability. Tests of the VTBB100 have shown a high stability of the VTBB100 temperature control, providing accurate maintenance of the radiator temperature to about 10 mK. The temperature difference in the measured zones  $T_1 - T_5$  does not exceed 10 mK over the whole range of working temperatures of the radiator.

Computer simulation has confirmed that the design and thermophysical parameters of the VTBB100 were chosen appropriately. Tests of the temperature homogeneity of the real system have confirmed the results of model calculations.

## 5 Results of the VTBB100 Effective Emissivity Modeling

The numerical investigation of the effective emissivity of the VTBB100 is performed by means of STEEP3 modeling software based on the Monte-Carlo algorithm [5]. The calculation of a normal effective emissivity  $\varepsilon$  for the radiator cavity of VTBB100 was conducted for the temperature range from 100 K to 450 K. In the spectral range from 4  $\mu\text{m}$  to 24  $\mu\text{m}$ , the average value of the diffusivity  $D$  of the Z306 paint [6] is 0.82, which results in an average value of 0.95 for the emissivity,  $\varepsilon$ . The value of the normal effective emissivity for the isothermal case with a diffusivity  $D = 0.82$  and a coating emissivity of  $\varepsilon = 0.95$  is 0.999948. Calculations of the normal effective emissivity were performed for cases where the non-uniformity of temperature along the radiator cavity varies from 10 mK to 100 mK.

If the non-uniformity of the temperature on the bottom of the cavity is no more than 10 mK (Fig. 4), the normal effective emissivity of the cavity at 150 K in the spectral range from 7  $\mu\text{m}$  to 25  $\mu\text{m}$  is no less than 0.9997.



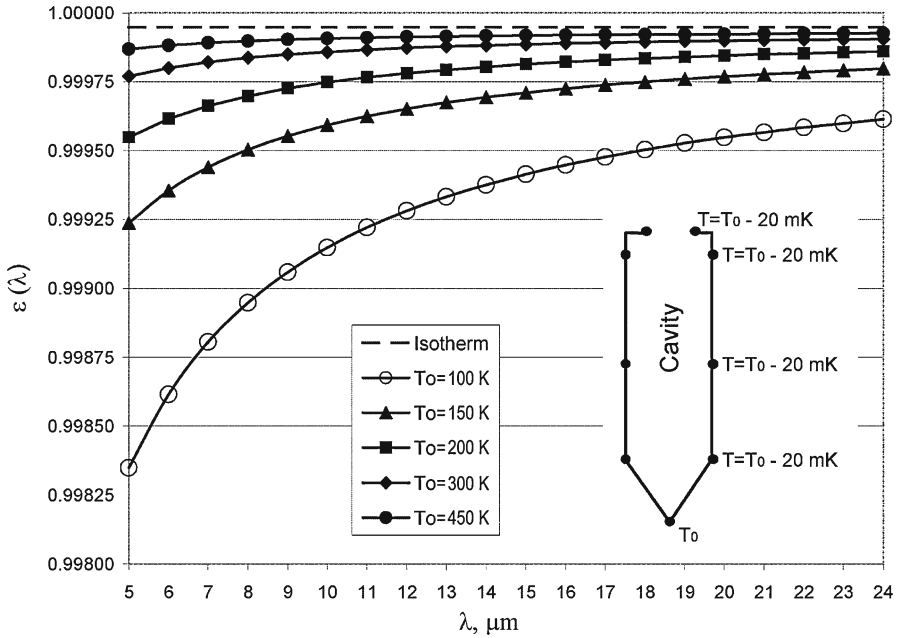
**Fig. 4** Dependence of the effective emissivity  $\varepsilon(\lambda)$  from a non-uniform temperature distribution along the radiator cavity ( $\Delta T = 10$  mK) at multiple temperatures

If the non-uniformity of the temperature of the radiator cavity is no more than 20 mK (Fig. 5), the normal effective emissivity of the cavity at 150 K in the spectral range from 10  $\mu\text{m}$  to 25  $\mu\text{m}$  is no less than 0.9996. An increase of the temperature gradient along the cylindrical part of the cavity has practically no influence on the normal effective emissivity (Fig. 6). It is therefore very important to ensure the temperature homogeneity of the bottom of the radiator cavity.

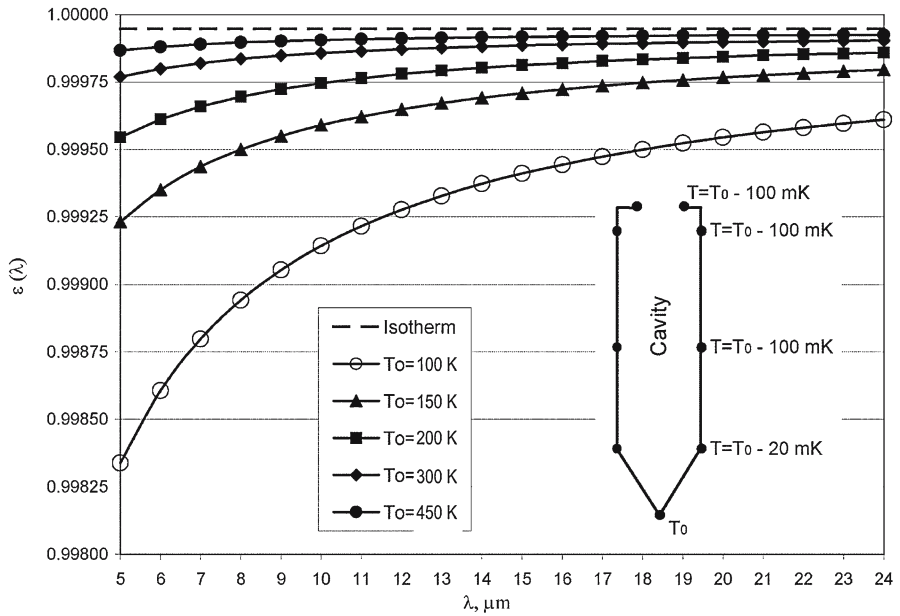
## 6 VTBB100 Electronic System

The block diagram of the VTBB100 temperature control is presented in Fig. 7. The main units of the BB100 electronic system are: precision temperature controller, current amplifier units, screen temperature controller, computer, digital multimeter with multiplexer, Hart Scientific Superthermometer, and a system to supply liquid nitrogen. The temperature control of the three-zone VTBB100 is provided with the help of two controllers: a screen temperature controller (based on the Micromega CN 77000) and a precision temperature controller (based on the EUROTHERM 2604 controller). The screen temperature controller is used for coarse temperature control of the blackbody by heating or cooling the cryo-shroud around the VTBB100 cavity. The temperature of the cryo-shroud is monitored with Pt resistance thermometer; T8, T1, T2, T2a, T3, T3a, and T4 precision resistance thermometers are used for precision temperature measurements with the Hart Scientific Superthermometer. T5, T6, and T7 precision resistance thermometers are used for accurate temperature measurement

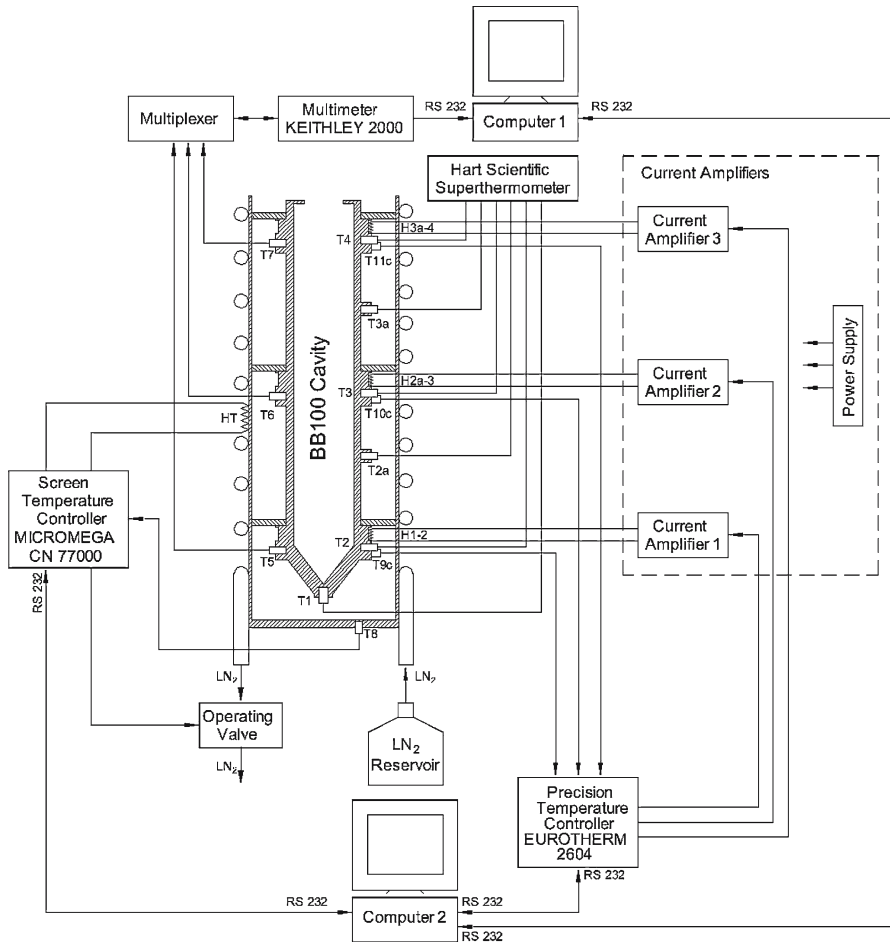




**Fig. 5** Dependence of the effective emissivity  $\varepsilon(\lambda)$  from a non-uniform temperature distribution along the radiator cavity ( $\Delta T = 20$  mK) at multiple temperatures



**Fig. 6** Dependence of the effective emissivity  $\varepsilon(\lambda)$  from a non-uniform temperature distribution along the radiator cavity ( $\Delta T = 100$  mK) at multiple temperatures



**Fig. 7** Schematic diagram of the temperature measurement and control system of the VTBB100

with the digital multimeter and multiplexer. Values of temperature from these three thermometers are used for the change in set-point temperature of each zone of the precision temperature controller EURO THERM 2604, including the three-control-loop PID. For fine correction of the VTBB100 temperature stabilization, T9c, T10c, and T11c fast resistance thermometers are used with the precision temperature controller EURO THERM 2604. The selected configuration of this device contains three signal-conditioning units for the platinum resistance thermometers T9c, T10c, and T11c, three analog output circuits, and a serial interface (RS232) for connection to the computer. The voltages from the outputs of the analog circuits of the Eurotherm controller program the outputs of the current amplifiers that drive the heaters H1-2, H2a-3, and H3a-4. The resistances of the precision thermometers T5, T6, and T7 are measured using a four-wire technique by the Keithley 2000, ensuring the absolute accuracy of the measurements ( $5 \times 10^{-5}$ ). These values of temperature are transmitted

to the computer on a serial channel. The correction of temperature in every zone is performed at the expense of changes to the set-point temperature  $T_{SP(Ni)}$  for each zone ( $N = 3$ ) with the help of the formula,

$$T_{SP(Ni)} = (T_{SP\text{ abs}} - T_{Ni\text{ KEITHLEY}}) \times K + T_{EUROTH}, \quad (5)$$

where  $T_{SP(Ni)}$  is the new value of the set-point temperature in a specific control loop;  $T_{SP\text{ abs}}$  is the absolute value of the set-point temperature for the blackbody;  $T_{Ni\text{ KEITHLEY}}$  is the current value of temperature measured by the Keithley multimeter in the same zone;  $K$  is the amplification gain; and  $T_{EUROTH}$  is the current temperature indicated by the EUROTHERM 2604 in the zone.

## 7 Conclusions

Experimental investigations of the VTBB100 characteristics carried out at PTB have demonstrated the efficiency of the method of the set-point temperature correction in the three-zone system of blackbody temperature control based on the three-channel Eurotherm 2604 temperature controller. This method allows the blackbody temperature to be established and maintained with high accuracy for a long time. The instability of the VTBB100 radiating temperature does not exceed 20 mK over the whole temperature range. Temperature differences along the cavity measured by the six PRTs do not exceed 20 mK, providing high effective emissivity of the blackbody. Such characteristics of the VTBB100 allow its use as a highly stable reference source for the calibration of blackbody sources in the temperature range from 100 K to 450 K.

The high stability and homogeneity of the emissivity of the VTBB100 also allows it to be used as a reference blackbody when measuring the emissivity of different materials in the temperature range from 100 K to 450 K under medium-vacuum conditions ( $10^{-3}$  Pa) in a medium-background environment (liquid-nitrogen-cooled shroud).

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