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DEVELOPMENT OF NEW BLACKBODIES FOR TEMPERATURE AND RADIOMETRIC CALIBRATIONS

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Abstract: The paper describes in details three newly developed cavity-type blackbody models with variable working temperature for radiometry and thermometry calibrations within -60 ^{0}C to 2000 ^{0}C temperature range: BB2000/40, BB1200/10, BB100 series, and a universal high-temperature furnace for operation with Cu and Ag-containing removable fixed-point crucibles.

Keywords: blackbody; furnace; emissivity; fixed points; radiation thermometry.

1. INTRODUCTION

The range of working temperatures of different blackbody (BB) models developed at VNIIOFI is located within 80 K to 3500 K. Constructively these BBs represent as variable-temperature models (both plane- and cavity-type), so as the BBs shaped in a form of crucible realizing temperature fixed points of melting/freezing phase transitions of pure materials – metals and metal-carbon eutectic and peritectic alloys. At typical values of effective emissivity from 0.998 to 0.9999 the apertures of VNIIOFI-made BBs vary within 3 mm to 350 mm. The BB sources were designed as for operation under low-background conditions of cryogenic chamber modeling orbital spaceflight, so for operation at open-air conditions. Besides VNIIOFI, low- and high-temperature BBs work as a part of a highest-precision facilities at such metrological centers as NIST (USA), PTB (Germany), NPL (UK), LNE/CNAM (France), AIST/NMIJ (Japan), KRISS (Korea), NIM and IAO (China), SCEI (Singapore), NPL (India) e.a., and also in space research centers SDL (USA), DLR (Germany), NEC-Toshiba Space (Japan). In Russia VNIIOFI-made BBs are functioning now at VNIIM, Keldysh Space Center, RNIIKP/RISDE, NPO GIPO and others.

The paper describes some of BBs developed at VNIIOFI for the last time [1-5] from low (about -60 ^{0}C to 90 ^{0}C) to medium (250 ^{0}C to 900 ^{0}C) and high (900 ^{0}C to 2000 ^{0}C) temperature regions for calibration of the radiometers and radiation thermometers under vacuum and open-air environment conditions.

2. GRAPHITE-CAVITY BB2000/40 BLACKBODY

High temperature BB2000/40 blackbody with the cavity made of graphite and pyrographite (PG) combination was developed as a universal instrument for calibration of radiation thermometers and thermocouples.

Operating within the temperature range from 900 °C to 2000 °C, the blackbody has a wide cavity opening of 40 mm. External view of BB2000/40 is presented in Figure 1. Emissivity of the cavity, with PG heater rings replaced partly by graphite elements, was estimated as 0.998 ± 0.0015 in the spectral range from 350 nm to 2000 nm. The uniformity along the cavity axis, accounting for 10 °C, was measured using a B-type thermocouple at 1500 °C. Temperature uniformity across the bottom does not exceed 1 ^{0}C.

Modifications of the PG furnace, where PG heater rings are replaced partly or totally by graphite elements extend the lifetime of the heater, reduce the cost for some applications and, for some cases, improve the temperature uniformity.

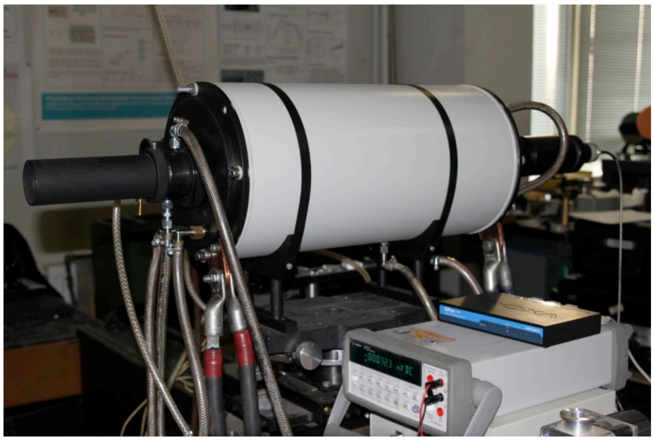

FIGURE 1. External view of BB2000/40 with an aperture extended hood mounted on its front electrode equipped with gas shutter (see left side of the instrument).

The BB2000/40 source can be used as precise Planckian radiator or as a furnace for fixed-point applications. Another advantage of the BB is an opportunity to modify it by replacing the graphite radiator with a set of PG rings in order to reach temperatures as high as 3200 ^{0}C. The latest development suggests more opportunities for potential users of the BB-type blackbodies.

Possibility of the BB2000/40 usage to calibrate high-temperature thermocouples by means of crucibles featuring cavity dimensions of 6 - 8 mm aperture and 60 - 70 mm depth, is studied.

3. BB1200/10 BLACKBODY

The BB1200/10 source with output aperture of 10 mm (see Figure 2) was developed for operation within 250 ^{0}C - 950 ^{0}C temperature range. The main application of the BB is a source of IR radiation of the known temperature for the purpose of radiometry and thermometry. Effective emissivity of radiating cavity accounts for 0.998, and the temperature reproduction uncertainty is about 0.25%.

The BB1200/10 in different versions was designed for several Russian research institutions and metrological centres. BB features radiating cylinder-shaped cavity made of nickel-chromium heatproof alloy. External surface of the radiator is equipped with a coil supplying its uniform heating. The heater along with thermo shield is place in a housing made of aluminium alloy equipped with circular ribs for enhanced cooling. By request, the BB may be equipped with removable precise apertures.

FIGURE 2. The view of BB1200/10 blackbody with radiating cavity made of nickel-chromium heatproof alloy.

4. COPPER FIXED-POINT BLACKBODY

It is of a great importance to develop «mise en pratique» (practical) thermodynamic temperature scales in connection with the ITS-90 equipment calibration standard on the basis of high temperature fixed points (HTFP) of pure materials' phase transitions determined by means of primary thermometry technique. The most significant fixed point for scale extrapolation into high-temperature range (for instance up to 3200 ^{0}C) is the temperature of copper solidification phase transition (1084.62 ^{0}C).

In order to carry out thermometers calibration with maximal accuracy, one should utilize materials with purity of at least 6N (99,9999%). At this, the realized fixed-point temperature will have a discrepancy with the phase transition temperature of ideal pure material of no more than 1 mK. Divergence of fixed-point temperature with the value assigned in ITS-90 depends on the kind of impurities and their interaction with specified metal. According to estimations, if a metal of 5N-purity is utilized, then for Al, Ag, Au, Cu metals the mentioned above discrepancy does not exceed some mK.

The new precise high temperature cavity-type optical radiation source was developed at VNIIOFI, utilizing removable graphite crucibles containing HTFP binary eutectic alloys or pure metals Al, Ag, Cu. Development of such blackbody source on the basis of copper HTFP for calibration of radiation thermometers and PRT-sensors was due to the reason that we participate in the international Project «HTFP» of Working Group-5 of CCT BIPM aimed on investigation of such high temperature fixed-points as Re-C, Co-C, Pt-C, WC-C and Cu. This cavity-type blackbody features the universal design with the possibility to insert graphite crucibles containing binary eutectic alloys or pure metals. The main features of the BB with installed HTFP crucible filled with pure copper are presented in Table 1.

TABLE 1.
Characteristics of Cu fixed-point cavity type BB

Working temperature	1084.62 ^{o}C
Size of output aperture	3 mm
Effective emissivity	not less than 0.9997
Power consumption	0.6 kW

The value of emissivity of the BB was calculated by means of Monte Carlo statistical modeling of ray tracing within a radiating cavity, with the usage of STEEP-3 (ver.1.3) software from Virial Co. The modeling took into account the following geometry of BB cylindrical cavity: length of 35 mm, inner diameter of 5 mm, and conical bottom with 120^0 apex angle. The inner surface of the graphite cavity was assumed with absorption factor of 0.8. As the result, the calculated value of effective emissivity of isothermal radiation cavity accounts for ε_{eff} = 0,99971696. Figure 3 presents the cross-section of the crucible with inner cylindrically shaped radiating cavity surrounded by the volume filled with pure material - Cu, Ag or any binary eutectic or peritectic alloy serving as HTFP.

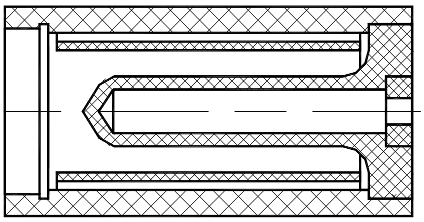

FIGURE 3. Drawing of graphite crucible-blackbody containing HTFP on the basis of melting/solidification phase transition of pure metal or eutectic binary alloy. Material of crucible – purified MPG6 graphite of high density

Structurally the furnace consists of radiating block, power supply / control block and removable BB-crucibles, that significantly enhances the possibility to incorporate the furnace in different thermometry and radiometry facilities. The crucible and radiating cavity are manufactured of graphite.

Heating of the crucible is carried out by means of wire heater made of Khantal with working temperature 1400 ^{0}C.

The wire heater contains graphite block of a special design supplying high longitudinal temperature uniformity along the cavity. Utilization of such a block gives the possibility to have a single heating zone only. This graphite block contains type-S thermocouple supplying a temperature feedback for control block correct operation. The longitudinal cross-section of the BB is shown in Fig.4.

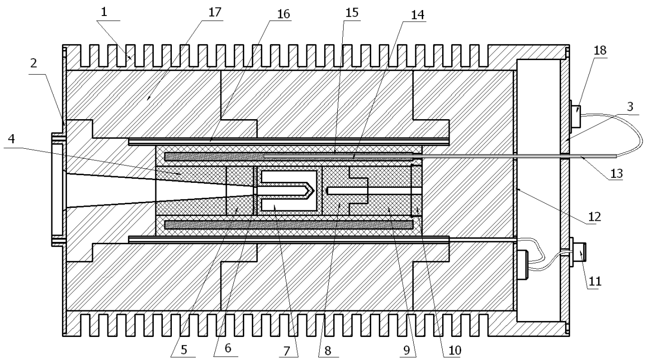

FIGURE 4. Drawing of cavity-type blackbody assembled with inserted radiating cavity surrounded by pure metal or binary eutectic serving as HTFP.
Legend: 1 – housing, 2. - front flange, 3. rear flange, 4 - front insulation, 5 - front insertion, 6 – aperture, 7 - graphite crucible, 8 - rear insertion, 9 - rear insulation, 10 - rear wall, 11 - heater connector, 12 – cover, 13 – thermocouple, 14 - graphite fabric, 15 - copper heater, 16 - ceramic insulator, 17 - high temperature thermal insulation material TZMK on the basis of silicon fibre, 18 - thermocouple connector

The heater is surrounded by thermo shield made of thermal insulation ceramic-type material TZMK on the basis of silicon complex (SiO_2+Al_2O_3) fibre with working temperature exceeding 1400 ^{0}C. The usage of such highly efficient constructive and insulating material allowed to refuse from water cooling or a housing of a bulky design. The BB does not require any output window during operation at working temperatures. In order to avoid graphite evaporation at high temperature, Argon gas purge is provided. During heating/cooling to or from working temperature, and also between measurement sessions the output aperture can be covered with removable Silicon glass window, which allows reducing gas consumption and eliminating graphite evaporation.

The temperature of copper heater block is kept with a high accuracy be means of temperature controller JUMO cTRON of 702071/8-1130-23-00 type. It utilizes type-S thermocouple as a probe incorporated in the copper heater block. The temperature controller provides 2 ^{o}C accuracy of temperature set point with 0.2 ^{o}C measurement uncertainty at temperature level maintenance. Precise BB temperature operation allows flexible control of melting/solidification processes. Set-point temperature keeping accuracy is generally defined by the chosen type of temperature controller, and can be improved to about 0.1% at use of better tool.

BB housing is made of aluminium alloy with cooling ribs. The fan is applied to more effective cooling of the case. Power supply and temperature controller are placed in a standing alone block, that that facilitates BB operation. External view of copper fixed-point BB is shown in Figure 5.

FIGURE 5. The view of copper fixed-point blackbody during tests.

As it was discovered during tests, the time of working temperature (1050 - 1100 ^{0}C) achievement after BB turning on, does not exceed 60 minutes. Duration of temperature transition from one set point to another at 10 ^{0}C-temperature change does not exceed 10 minutes. Duration of a cooling from working temperature to 400 ^{0}C (the temperature level when it is possible to cut off Argon gas purge and turning off the BB), does not exceed 2 hours. Temperature drop of melting plateau (melting range) accounts for 10 mK at the plateau duration of 35 minutes. The same for solidification plateau is less than 10 mK for about 30 minutes.

5. VACUUM BLACKBODY OF BB100-V1/K1 SERIES

Blackbodies of BB100 series with 100-mm aperture (see Figure 6) were designed in order to supply radiometry and thermometry calibrations in the temperature range from -30 ^{0}C to 80 ^{0}C, as in “open-air” environment, so as under cryo-vacuum conditions. The working temperature range of the BB is mostly defined by the chosen type of thermostat and heat-transfer agent and, for example, can be -60 ^{0}C to 90 ^{0}C during operation in vacuum chamber. BB100 emissivity accounts for the value of 0.997 that was obtained with the usage of black cover paint Nextel Velvet 811-21, non-uniformity across the aperture is less than 0.05 ^{0}C, and instability of set-point temperature keeping is about 0.01 ^{0}C.

Different modifications of BB100 series were developed for Keldysh Space Center, NEC-Toshiba Space and KRISS. In particular, the special design of this BB was developed for operation at open air and in the atmosphere of inert gas or under dry air conditions. The similar to BB100-K1 design, featuring a special hood avoiding atmospheric oxygen suction into the heated cavity during operation, is now utilized at VNIIOFI.

BB100-series blackbody, the BB100-V1 was designed at VNIIOFI for calibration of space-borne radiometric instruments at NEC TOSHIBA Space Systems, JAXA (Japan), and Keldysh Space Center. It is an extended-area blackbody for low temperatures (250 K up to 350 K), which operates under cryo-vacuum conditions.

The BB100-V1 cavity is made of copper. The value 0.997 of emissivity was obtained with the usage of black cover paint Nextel Velvet 811-21.

Outer diameter of blackbody housing accounts for 214 mm. Length of radiating cavity is 200 mm. Overall length of BB100-V1, including nozzles (nuts) of copper heat exchanger tubing, accounts for 500 mm. Cross-section of the blackbody is shown in Figure 7. Temperature control of BB100-V1 is based on the utilization of the liquid circulation-type thermostat. Radiating cavity of BB100-V1 blackbody features cylindrical shape of 120 mm diameter. The screen-vacuum insulation around black radiating cavity is made of multi-layered polyethlenetheraftalat film. BB100-V1 is assembled in external housing made of stainless steel.

FIGURE 6. BB100-K1 low temperature blackbody as a set with liquid thermostat HUBER Unistat-750

Radiating cavity of BB100V1 blackbody contains five PRT-100 temperature sensors for uniformity temperature monitoring. Three of them are incorporated in the back side of V-grooved copper bottom, and two others – in the cylindrical walls. Besides this, the 5-th sensor is enabled in the feedback loop of temperature stabilization system based on thermostat controller. The reference PRT-100 temperature sensor for temperature monitoring was specially made removable with special holder in order to supply the possibility of its time-to-time recalibration, it is placed in the centre of the external (back) side of V-grooved bottom of radiating cavity of BB100-V1.

The temperature uniformity and long-term stability account for less than 0.1 K and 0.1% for 1.5 µm to 15 µm wavelength region under cryo-vacuum conditions of medium background environment.

Temperature uniformity of the BB100-V1 across the cavity bottom does not exceed 40 mK and 100 mK along the cavity wall.

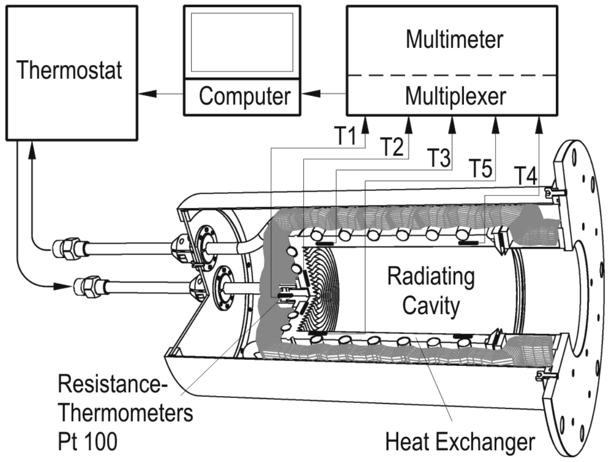

FIGURE 7. Cross-section of BB100-V1 blackbody.

6. ACKNOWLEDGEMENTS

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