RADIATION THERMOMETRY, THERMODYNAMIC TEMPERATURE AND EMISSIVITY MEASUREMENTS AT THE PTB – AN OVERVIEW

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Abstract: To meet the increasing demand of calibrations in the field of radiation thermometry, the Physikalisch-Technische Bundesanstalt (PTB) operates two different setups for calibrations covering the temperature range from -60 °C up to 3000 °C. The first setup consists of several heat-pipe blackbodies in conjunction with platinum resistance thermometers, calibrated according to the International Temperature Scale of 1990 (ITS-90) and is applied for calibrations in the temperature range from -60 °C to 961.78 °C. In the temperature range from 962 °C to 3000 °C the calibration is based on high temperature blackbodies. The temperature of these blackbodies is determined in two independent ways: traceable to the ITS-90 gold fixed point or via absolutely calibrated filter radiometers (FR) traceable to the detector primary standard, the cryogenic radiometer. Taking advantage from the high accuracy of the FR calibration, these FRs have also been successfully used for the investigation of the thermodynamic accuracy of the ITS-90 in the range from 419 °C to 962 °C. For non-contact temperature measurements, the emissivity of the observed object is one of the most important parameters. Therefore, PTB has set up instrumentations for measuring the directional spectral and total emissivity of samples in air from 80 °C up to 400 °C over a spectral range from 4 µm to 40 µm and under vacuum from 0 °C to 600 °C and in the spectral range from 1 µm to 1000 µm.

1. INTRODUCTION

Temperature governs most of the technological processes in industry, its measurement being of crucial importance for an optimized productivity and a long-term quality assurance.

Frequently, radiation thermometry is used as a temperature measurement technique. The applied instrumentation for this non-contact method are radiation thermometers, which usually work in the so-called "atmospheric windows" wavelength ranges, typical at 1.3 µm, 1.6 µm, 3 µm to 5 µm and 8 µm to 14 µm. Conditioned by the progressing globalization in science and industry, to ensure a worldwide comparability of the measured temperatures performed with different instruments or of measurements collected over a long period of time with the same instrument, it is mandatory to calibrate the radiation thermometers traceable to SI-units. In general, radiation thermometers are calibrated by means of blackbodies, serving as high accuracy radiation temperature sources. To fulfill the traceability requirement, the temperature of these blackbodies is determined according to the International Temperature Scale of 1990 (ITS-90) as a close approximation of the thermodynamic temperature i.e. the SI base unit Kelvin. Alternatively, the true thermodynamic temperature of the blackbodies can be determined directly with absolute radiometric methods by using calibrated detectors with known spectral responsivity.

## 2. THERMODYNAMIC TEMPERATURE DETERMINATIONS

For more than a decade, the PTB performs absolute thermodynamic temperature determinations of blackbodies by applying absolutely calibrated filter radiometers (FRs). The main motivation for this task is the investigation of the thermodynamic accuracy of the ITS-90 i.e. the difference between thermodynamic temperature T and ITS-90 temperature T_{90} (T-T_{90}), in the temperature range from the tin fixed point (Sn-FP, 232.928 °C) to the silver fixed point (Ag-FP, 961.78 °C) [1-6].
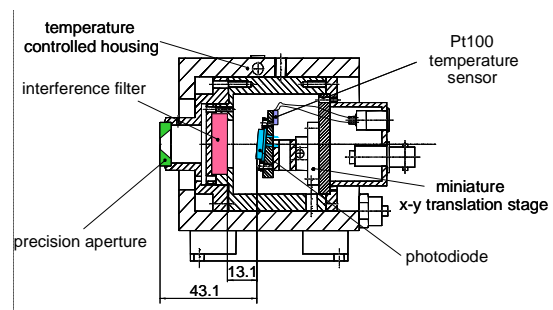
Fig. 1 *The interference filter based radiometer applied at the PTB for thermodynamic temperature determinations (schematic view).*

In parallel, these FRs are used as an independent, detector based method for the thermodynamic temperature determination of the high temperature

blackbodies employed for the dissemination of radiation temperatures above the Ag-FP (section 3.2) [7]. The FRs are used in irradiance mode (figure 4) and consist basically of a precision aperture, an interference filter as the wavelength selecting element and a silicon-photodiode (Si-PD) or an indium-gallium-arsenide-photodiode (InGaAs-PD) as the radiation detector (figure 1).
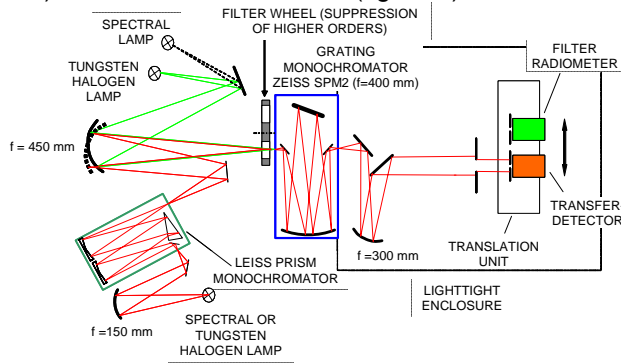
Fig. 2 *Schematic view of the PTB spectral comparator facility for the absolute calibration of filter radiometers in terms of spectral irradiance responsivity*

The calibration of the FR in terms of spectral irradiance is a two step procedure. First a transfer detector (TD), typically a Si-PD trap detector [8] or a single InGaAs-PD, is calibrated for its spectral responsivity against the detector primary standard of PTB, the cryogenic radiometer [9, 10]. In combination with a precision aperture of known area [11] the TD is transformed from a spectral responsivity standard into a spectral irradiance responsivity standard. The second step comprises the calibration of the FRs in terms of their spectral irradiance responsivity by direct comparison against the TD at the Spectral Comparator Facility of PTB (figure 2) [12,13].
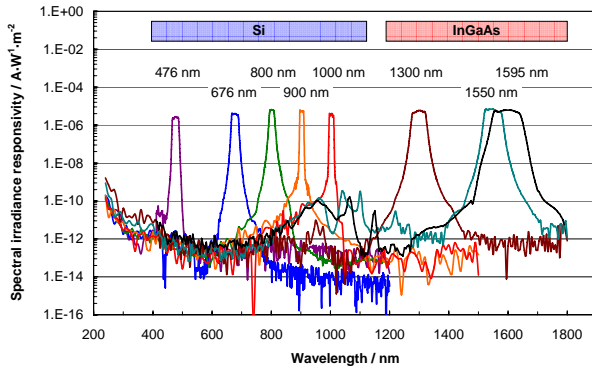
Fig. 3 *The spectral irradiance responsivity of the Si- and InGaAs-photodiode based filter radiometers of the PTB.*

Figure 3 gives an overview of the calibrated spectral irradiance responsivity and the centre wavelength of the FRs used for thermodynamic temperature determinations at the PTB. The spectral bandwidth varies from about 20 nm (Si-PD) up to about 100 nm (InGaAs-PD), the out-of-band blocking is better than 10^{-5}. The achievable relative standard uncertainty (k=1) of the FR spectral irradiance responsivity calibration depends on the centre wavelength and ranges from 0.03 % to 0.06 % for the Si-PD based FRs and from 0.06 % to 0.14 % for the InGaAs-PD based FRs.

After their calibration, the FRs are applied for thermodynamic temperature determination according to the experimental setup depicted in figure 4.
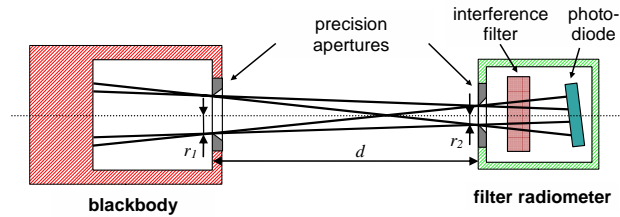
Fig. 4 *Schematic view of the experimental setup for the measurement of the thermodynamic temperature with filter radiometers*

The measured photocurrent I_{photo} is equal to

$$I_{photo} = \varepsilon \cdot G(r_1, r_2, d) \cdot \int s_{E,FR}(\lambda) \cdot L_{\lambda,BB}(\lambda, T) d\lambda \quad (1)$$

with ε the emissivity of the blackbody, $s_{E,FR}(\lambda)$ the spectral irradiance responsivity of the FR, $L_{\lambda,BB}(\lambda, T)$ the spectral radiance of the blackbody at the temperature T according to Planck's law and $G(r_1, r_2, d)$ the geometrical expression according to:

$$G = \frac{2\pi r_1^2}{r_1^2 + r_2^2 + d^2 + \sqrt{(r_1^2 + r_2^2 + d^2)^2 - 4r_1^2 r_1^2}} \quad (2)$$

From equation 1, the thermodynamic temperature T of the blackbody is calculated iteratively.

The first results for T-T_{90} at the PTB in the temperature range from the Al-FP to the Ag-FP were obtained employing two Si-PD based FRs with centre wavelengths at 676 nm and 800 nm in conjunction with a sodium double heatpipe black-body as a high accuracy radiation source [1, 14]. After a significant improvement of the accuracy of the spectral responsivity scale up to 1020 nm [9], two new FRs with centre wavelength at 900 nm and 1000 nm were calibrated and then successfully used for T-T_{90} measurements in the temperature range from the Al-FP to the Zn-FP [2, 3]. For the extension of the T-T_{90} measurements down to the Sn-FP, a shift of the centre wavelength to the near infrared (NIR) was mandatory. After the PTB had extended its high accuracy spectral responsivity scale up to

1.7 µm [10], disseminated on single InGaAs-PDs, InGaAs-PD based FRs with a completely new design and centre wavelengths at 1.3 µm, 1.55 µm and 1.595 µm (figure 3) were constructed and calibrated with uncertainties comparable to the existing Si-PD based FRs. In the temperature range from the Zn-FP to the Al-FP an excellent agreement was found for the measurement results of T-T_{90} between the two types of FRs [5, 6].

3. RADIATION THERMOMETRY

3.1 Low and medium temperature scale

For the realization and dissemination of the temperature scale in the temperature range from -60 °C to 961.78 °C (silver fixed point) for radiation thermometry applications, the PTB applies four different, variable temperature heat-pipe blackbodies with large apertures. A schematic view of the low- and medium temperature calibration facility, including the main parameters of the applied blackbodies is given in figure 5 [15]. The traceability of the radiation temperatures to the ITS-90 is realized via calibrated standard platinum resistance
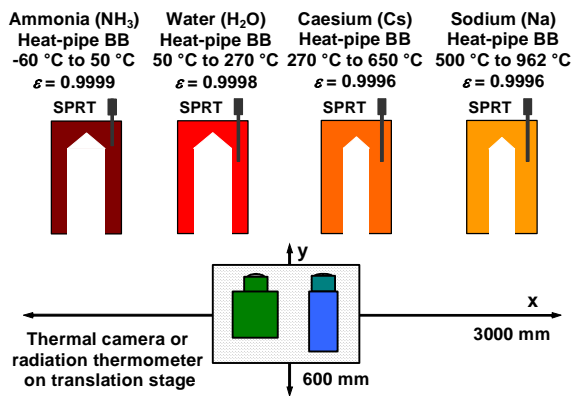
Fig. 5 *The low- and medium temperature scale calibration facility of the PTB (schematic view)*

thermometers (SPRTs) sensing the temperature close to the bottom of the cavities. Customized temperature stabilization systems allow all of the blackbodies to be operated with a temperature stability of ± 10 mK. The calibration artifacts, for example radiation thermometers or thermal cameras, are positioned by means of a three axis translation system in front of the side by side arranged blackbodies.

Table 1 summarizes the standard uncertainties (k=1) for the realized radiation temperatures at the low temperature calibration facility of the PTB with

respect to typical wavelengths of radiation thermometers.

Table 1 *The standard uncertainties (k=1) for the realized radiation temperatures at the low-temperature calibration facility of the PTB, given for common radiation thermometers wavelengths*

Temperature / °C	Standard uncertainty of radiation temperature (k=1)/°C		
	1.6 µm	3.9 µm	10 µm
-60		0.1	0.035
0	0.035	0.035	0.035
50	0.035	0.035	0.035
100	0.035	0.035	0.035
200	0.08	0.08	0.08
300	0.1	0.10	0.10
400	0.02	0.03	0.05
600	0.03	0.05	0.08
800	0.06	0.07	0.11
960	0.08	0.10	0.14

3.2 High temperature scale

Above the silver fixed point to about 3000 °C the realization and dissemination of the radiation temperature scale of the PTB relies on two blackbody radiation sources [7, 15].
The first blackbody is an ITS-90 gold fixed point blackbody (Au-FP BB) with an emissivity of 0.99999, emitting thermal radiation at 1064.18 °C. During the 90 minutes duration of the freezing period, an outstanding temperature stability of about 10 mK can be achieved, yet with the limitation to one fixed temperature.
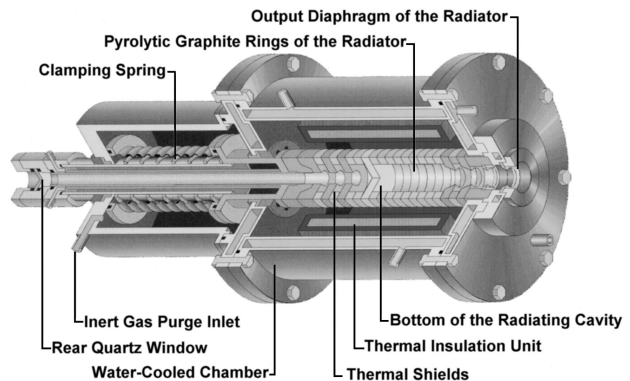
Fig. 6 *The high-temperature blackbody HTBB3200pg*

To overcome the one temperature limitation of a FP BB, the Au-FP BB is complemented by a

variable, high-temperature blackbody (HTBB) of type BB3200pg operating in the temperature range from 950 °C to 3000 °C with a temporal stability of the radiation temperature of better than 300 mK. A cross section view of the HTBB is displayed in figure 6. Its cavity, made of pyrolitic graphite, is directly Joule-heated and has a calculated emissivity of 0.999.

Both blackbody radiation sources are implemented in the Spectral Radiance Comparator Facility (SRCF) of the PTB [7] and used for the calibration of source standards of radiation temperature (ex. tungsten strip lamps) and radiation thermometers. The functional schematic of the SRCF is shown in figure 7.
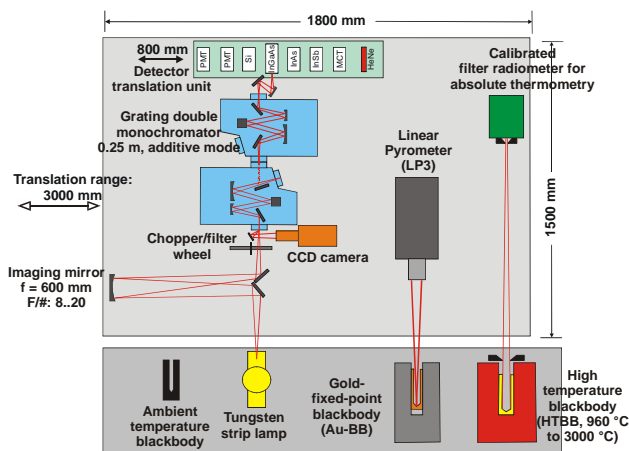
Fig. 7 *Schematic view of the Spectral Radiance Comparator Facility of the PTB*

Applying the HTBB for calibration, its temperature can be determined in two independent ways: either according to the ITS-90 by comparison with the Au-FP BB at any wavelength (T_{90}) or by measure-ment of the thermodynamic temperature T with absolutely calibrated filter radiometers as outlined in section 2. The standard uncertainty of the two temperature determination methods is about 0.2 °C at 1000 °C and 0.7 °C at 3000 °C

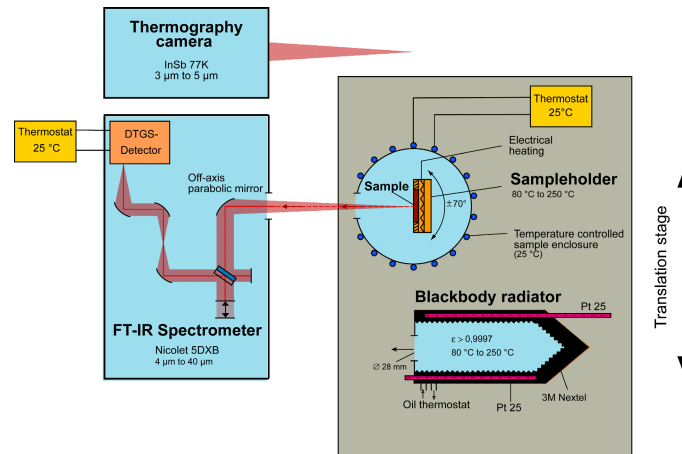## 5.   EMISSIVITY MEASUREMENTS

A broad variety of high quality radiation thermometers for specific temperature ranges and applications is on the market and the calibration of such thermometers traceable to the ITS-90 has been well established by now. Therefore, the lack in knowledge of the spectral emissivity of the observed object has become the major source of uncertainty in many industrial and scientific non-contact temperature measurements. The PTB has set up instrumentations for measuring the spectral and total

emissivity of samples in air from 80 °C up to 400 °C over a spectral range from 4 µm to 40 µm. Additionally, a new facility for emissivity measurements under vacuum has been constructed and will go into operation in the end of 2009 [16]. This new facility will allow measurements at a reduced uncertainty level and in an extended temperature and spectral range from 0 °C to 600 °C and from 1 µm to 1000 µm, respectively.

The dimensionless quantity directional spectral emissivity of a radiating sample is defined as the ratio of the spectral radiance of the sample to the spectral radiance of an ideal blackbody at equal temperature:

$$\varepsilon_\lambda(\lambda) = L_{\lambda,\text{Sample}}(T,\lambda) / L_{\lambda,\text{Planck}}(T,\lambda) \qquad (3)$$

The measurement principle at the PTB follows the definition of the emissivity in equation 3. The directional spectral emissivity of a sample is determined by measuring the spectral radiant power emitted by the sample with respect to the spectral radiant power emitted by a reference blackbody. Due to the constant geometry of detection for both sources this is equivalent to the determination of the ratio of the spectral radiances. Both measurements have to be done sequentially: the sample and the blackbody are alternately positioned in the detection area of the Fourier-transform spectrometer with the help of a translation stage (figure 8).

As the emissivity of a sample is usually not unity the sample, additionally, reflects part of the radiation emitted by the surrounding towards the spectrometer. By an isothermal surrounding of the sample at known temperature and with constant spectral emissivity - here realized by the spherical enclosure around the sample (compare figure 8) - the ambient radiation incident on the sample and consequently the emissivity of the sample can be determined [17].

Fig. 8 *The experimental setup for directional spectral emissivity measurements in air. It consists of a Fourier-transform spectrometer, a sample holder and a reference blackbody radiator, all temperature stabilized. The sample in the sample holder and the reference black body can be positioned via a translation stage in the measurement area of the spectrometer. The stage also allows the positioning of the sample and the blackbody in front of a thermography camera.*

ACKNOWLEDGEMENTS

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