A Facility for Spectral Emissivity Measurement under Vacuum for Industrial and Remote Sensing Applications

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Abstract

A variety of techniques for the measurement of emissivity is available today but in many cases these techniques do not adequately meet the wide range of requirements posed by modern science and industry. Furthermore, they do not provide sufficiently accurate results and lack reliable and traceable uncertainties. Therefore, a measurement setup and a validated method for highly accurate directional spectral emissivity, total directional emissivity and total hemispherical emissivity measurements under vacuum in the wavelength range from 4 µm to 100 µm and a temperature range from -40 °C to 600 °C with validated uncertainties was developed at the Physikalisch-Technische Bundesanstalt (PTB). Using a direct radiometric method with two reference blackbodies, the measurements at this facility, the Reduced Background Calibration Facility (RBCF), are traceable to the International Temperature Scale of 1990 (ITS-90).

1 Introduction

The unique potential of radiation thermometry for temperature measurements ranging from non-contact temperature control of industrial production processes to climate research by remote sensing of the Earth requires the accurate knowledge of the radiation properties of the observed material, i.e. its spectral emissivity. The spectral emissivity is not only essential to perform quantitative temperature measurement but also to precisely calculate radiative heat exchange. The accurate knowledge of the emissivity is required in many industrial and scientific applications like e.g. solar energy generation, modern furnace technologies, improved thermal insulation of buildings, high-temperature ceramics in high-temperature engines, cryogenic insulations and remote sensing of the Earth.

Simple and practical methods, for example described in VDI/VDE 3511-4 [1], often only provide a good approximation, but give no accurate result with a reliable uncertainty value. Using a newly developed facility for radiation thermometry under vacuum at PTB [2-4] directional spectral emissivity, total directional emissivity and total hemispherical emissivity measurements in a broad wavelength and temperature range can be performed highly accurate under vacuum with traceable uncertainties.

2 Setup

This facility (Fig. 1), the Reduced Background Calibration Facility (RBCF), is a unique metrology facility within Europe. In addition to precise emissivity measurements, it allows radiation temperature and spectral radiance measurements traceable to the International Temperature Scale of 1990 (ITS-90) over a broad spectral and wide temperature range. The operation under vacuum reduces significantly the uncertainty of measurements, since the heat losses by convection and the uncertainty from changing atmospheric absorptions due to varying partial pressures of H_2O and CO_2 are omitted here. Furthermore, reduction of the background radiation can be achieved by cooling of all apertures and critical optical components in the optical path with liquid nitrogen. If required measurements can also be performed under different pressures or under different gases.

The measurement scheme for emissivity is based on a comparison of the spectral radiance of a sample with the spectral radiances of two reference blackbodies at different temperatures. The sample is located inside of a temperature stabilized spherical enclosure [2-4].

The spectrally dependent uncertainty of the directional spectral emissivity is calculated via a Monte-Carlo-Method strictly according to the Guide to Uncertainty of Measurement (GUM). Since the uncertainty components usually depend on the individual measurement conditions the calculation is done individually for every single measurement [4].

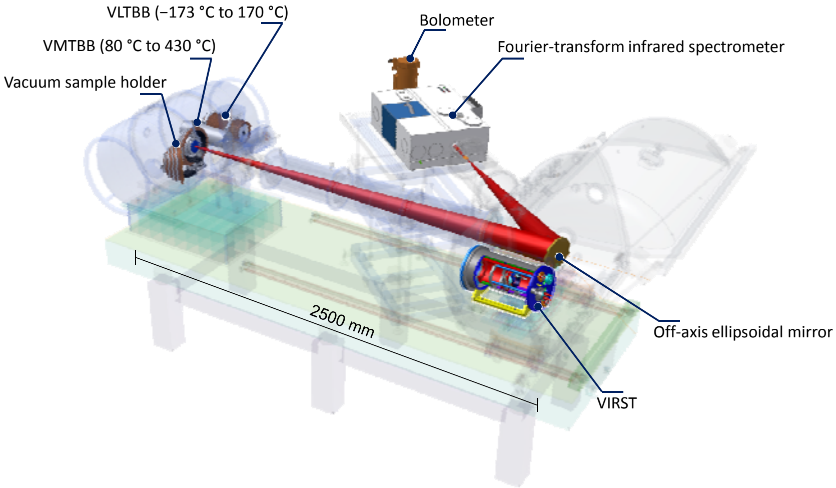

Fig. 1: Transparent view of the reduced background calibration facility (RBCF) to illustrate the positions of the blackbodies VLTBB and VMTBB, the vacuum sample holder for emissivity measurement, the vacuum infrared standard radiation thermometer (VIRST) and the optical path of the radiation in the LN_2-cooled beamline

3 Experimental results

Three examples were selected for this paper to illustrate the capability and potential of the new facility for determining the spectral emissivity and calibration of reference sources.

3.1 Emissivity of solar absorber coatings

An important application that requires very low uncertainties in the measurement of emissivity is the characterization of absorbers for high-temperature solar thermal energy generation. The potential of solar energy, as one of the major sources of renewable energy, has great relevance for economic growth and better environmental protection.

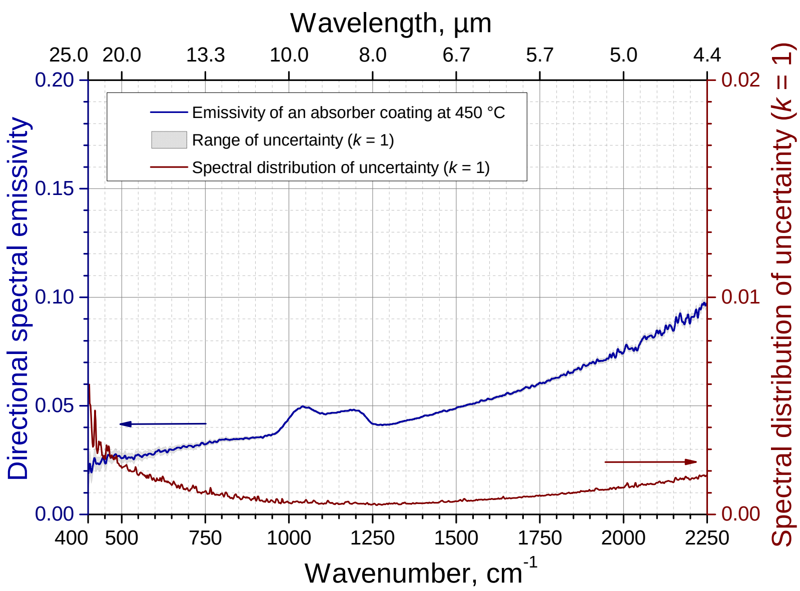

Fig. 2: Directional spectral emissivity of an absorber coating of SCHOTT Solar measured at a temperature of 450 °C and under an angle of observation of 10° with respect to the surface normal. The brown curve shows the spectral distribution of the standard uncertainty. The respective scale is shown on the right-hand ordinate axis

The development of solar energy technologies is connected to the optimization of the optical properties of absorber coatings - i.e. their solar absorptivity and thermal emissivity, which are key parameters for the efficiency of solar thermal power plants. Thus, a higher thermal efficiency of solar absorbers – directly yielding to significant economic benefits - can be provided by the reduction of the measurement uncertainty. The measurement of the emissivity of solar absorber coatings with an, until now, unrivaled absolute uncertainty in the MIR, where their emissivity is very low, was the major aim of this investigation at PTB.

The emissivity measurements have been performed in cooperation between PTB and SCHOTT Solar CSP GmbH (SCHOTT Solar) [5]. The measurements were done at a temperature of 450 °C and under vacuum, close to the real operating conditions of solar thermal power plants. The result under an angle of observation of 10° with respect to the surface normal is given in Fig. 2. The achieved uncertainty of the spectral emissivity is better than 0.005, as can be seen as brown curve.

3.2 High emissivity coating Aeroglaze Z306

With the precisely characterized reference blackbodies of the RBCF [4], emissivity measurements can be performed up to 100 µm. Currently, there is a lack of precise emissivity information in the FIR, even despite their increasing importance especially for wall coatings of reference sources. Those measurements become in particular important because of the increase of transparency of some coatings towards longer wavelengths.

One of such semi-transparent coatings, an absorptive polyurethane black paint Aeroglaze Z306, which is often used in aerospace operations, was chosen here as an example. Three samples were prepared by spray coating a set of three copper substrates in thicknesses of 44 µm, 99 µm and 236 µm. The measurements [4] were performed at a temperature of 150 °C. The directional spectral emissivities of the three samples under an angle of observation of 10° are shown in Fig. 3; the shaded areas illustrate the standard uncertainty for each measurement.

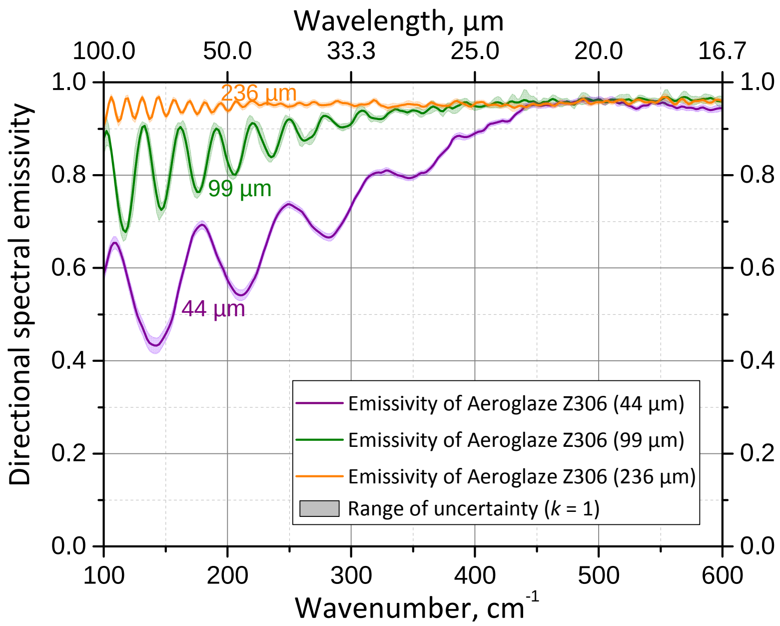

Fig. 3: Directional spectral emissivities of three Aeroglaze Z306 samples with thicknesses of 44 µm, 99 µm and 236 µm on copper substrates under an angle of observation of 10° with respect to the surface normal. The standard measurement uncertainties are shown as shaded areas

3.3 Large aperture on-board reference blackbodies

The characterization of coatings of onboard reference blackbodies for air and space-borne remote sensing missions is an another important field of emissivity measurement. The growing number of international projects, missions and initiatives underline the importance of the remote observation of the Earth's atmosphere and climate [6-8]. This is driven by the increasing impact of possible climate change on society, ecology and economy.

The improved uncertainties of the data derived from the remote sensing experiments directly improve the existing climate models and understanding of the climate of the Earth. It can be achieved by the lower radiometric uncertainties of the applied on-board reference blackbodies. Within this work the two large aperture on-board reference blackbodies of the GLORIA atmospheric limb-sounder were precisely characterized in terms of spectral radiance, emissivity and uniformity of the radiance temperature over the whole aperture of 100 mm by 100 mm traceable to the ITS-90 with an uncertainty of less than 100 mK (k=2) at temperatures down -50 °C to enabling the traceability of the atmospheric measurements of the GLORIA instrument. The measurements and results are described in detail in [9,10].

4 Conclusion

The successful realization and validation of a highly accurate facility and procedure to measure directional spectral, directional total and hemispherical total emissivities under vacuum has been accomplished at PTB. The low uncertainty according to the GUM and the operation in the broad wavelength range from 4 µm to 100 µm and the wide temperature ranges from -40 °C to 600 °C are the major achievements obtained with this work. All measurements are traceable to the ITS-90 using the direct radiometric comparison method of the spectral radiance of the sample with the radiance of the two reference blackbodies.

Important applications shown are the characterization of absorbers for high-temperature solar thermal energy generation under operating conditions. Here, the emissivity of the absorber was determined at a temperature of 450 °C and with an uncertainty of better than 0.005. In the field of climate research large aperture reference blackbodies for air and space-borne remote sensing missions to study the earth's climate changes were characterized with very low uncertainties of better than 100 mK (k = 2) at a temperature of -50 °C which is the state-of-the art for these type of blackbodies.

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