Infrared Physics & Technology 73 (2015) 275–280

Contents lists available at ScienceDirect

Infrared Physics & Technology

journal homepage: www.elsevier.com/locate/infrared

An emissivity measurement apparatus for near infrared spectrum

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HIGHLIGHTS

- A new emissivity measurement apparatus for near infrared spectrum is reported.
- We present an improved method to minimize the measurement error.
- The spectral emissivities of TA1, oxidized nickel and 304 austenitic stainless steel are measured and discussed.
- The uncertainty of the apparatus is discussed and calculated in detailed.

ARTICLE INFO

Article history:
Received 26 February 2015
Available online 20 October 2015

Keywords:
Spectral emissivity
Experimental apparatus
Near-infrared spectrum
Uncertainty

ABSTRACT

This study develops a new experimental apparatus for infrared spectral emissivity measurements which consists mainly of the following four parts: sample heating system, blackbody furnace, optical system, and data acquisition system. This apparatus focuses on the near-infrared spectral emissivity measurement covering the temperature range from 473 K to 1273 K and the wavelengths between 0.8 μm and 2.2 μm. The apparatus and the measurement method are described in detail, and an improved method is presented to minimize measurement error. The spectral emissivity of pure titanium TA1, oxidized nickel and 304 austenitic stainless steel are measured to validate the reliability and reproducibility of experimental apparatus. The experimental results in this study are in good agreement with those of other literatures. Various uncertainty sources in emissivity measurement are analyzed, and the combined standard uncertainty of this system is less than 3.9%.

1. Introduction

The infrared emissivity is a key material parameter of scientific implication and application in such areas as industrial production, aerospace industry, scientific research, radiation thermometry, telemetry and infrared guiding technique [1,2]. For example, in radiation thermometry, a 0.1 uncertainty in emissivity of a sample at 1273 K may correspond to a temperature error of about 35 K if the emissivity value is about 0.9, and the temperature error will reach 135 K if the emissivity value is about 0.2 [3]. The emissivity of materials is influenced by numerous factors including temperature, measuring wavelength, chemical composition, surface roughness and surface oxidation [4]. Even for the same material, the values of emissivity described in different literatures are sometimes different from each other. Therefore, it is necessary to investigate further the emissivity of materials and evolve with the improvement of measuring apparatus.

Many facilities about emissivity measurement have been described in the literature over the past decades [5–9]. The methods of these facilities can be broadly classified into two categories: indirect and direct emissivity measuring methods. Indirect measuring refers mainly to the reflection method [9] in which the emissivity can be calculated based on the Kirchhoff's law by measuring the reflectivity and the transmissivity of the sample [10]. Direct emissivity measuring method is based on the definition of emissivity by measuring the radiance of the sample and blackbody at the same conditions (e.g. temperature, wavelength and angle), in which the emissivity is computed as the ratio of the two measuring values. At present, direct emissivity measuring method often employs Fourier transform infrared spectrometer (FTIR) and monochromator. The former has such advantages as fast measurement and wide wavelength range [12], but the expensive cost makes it difficult to be introduced into general use. The latter is now widely employed to establish high-precision emissivity measurement systems owing to its advantages such as simple

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http://dx.doi.org/10.1016/j.infrared.2015.10.001
1350-4495/

and accurate principle, low cost, narrow width and high accuracy wavelength positioning [11,13–15].

The emissivity in near-infrared spectral range is commonly used in radiation pyrometers and fiber-optic colorimeters, and the reported data about this wavelength band is in shortage. Hence, it is significant to investigate the emissivity behavior of materials to enrich the emissivity data in this wavelength band. A new experimental apparatus is developed to provide accurate values of emissivity in near-infrared spectral ranges from 0.8 μm and 2.2 μm at the temperature between 473 K and 1273 K. A high-accuracy grating monochromator, a professional detector for near-infrared spectral range and a lock-in amplifier are employed to measure the normal spectral emissivity for solid materials accurately. Furthermore, in the past decades, most of the emissivity measurements were performed in the vacuum condition. But it is impossible to perform the radiation thermometry or other operations in such an ideal condition in practical use. For this reason, the effect of surface oxidation on the spectral emissivity needs to be taken into account, and the measurements are performed in atmospheric conditions to meet the operational conditions of interest in this research.

2. Experimental setup

The experimental apparatus as shown in Fig. 1 consists of the following parts: sample heating and temperature control system, blackbody furnace (ISOTECH R970), grating monochromator (omni-λ5007), lock-in amplifier (SR830) and optical chopper (SR540), two off-axis parabolic gold-coated mirrors, and motorized rotation stage. Radiation from the sample or blackbody is achromatically reflected from the off-axis parabolic gold-coated mirror 3 into a collimated beam. The collimated beam is then focused by another off-axis parabolic protected gold-coated mirror 4 and directed into the entrance slit of grating monochromator. Before reaching the entrance, the beam is modulated to an appropriate frequency by the optical chopper system to distinguish the intensity signal from background noise. In addition, a SD six-position optical filter wheel is installed in front of the entrance slit of grating monochromator to eliminate the impacts of secondary spectrum and stray radiation. Then the output signal is detected by a high performance InGaAs infrared detector at the spectral range between 0.8 μm and 2.2 μm, and the signal of the InGaAs detector is amplified by a lock-in amplifier and fed to data capture system. This design can effectively eliminate the noise signal and improve the accuracy of measurement.

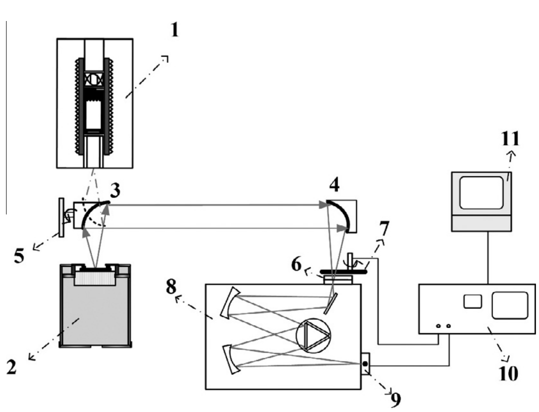

Fig. 1. Schematic diagram of the spectral emissivity measurement apparatus. 1 – Blackbody, 2 – sample furnace, 3 and 4 – parabolic gold-coated mirrors, 5 – motorized rotation stage, 6 – filter wheel, 7 – chopper, 8 – grating monochromator, 9 – detector, 10 – lock-in amplifier, and 11 – data capture system.

2.1. Blackbody

An ideal blackbody is defined as a source with the emissivity of 1 at all wavelengths and temperatures. However, the emissivity of actual blackbody is always less than 1. In order to meet the requirements of this system, the blackbody with high and stable emissivity should be chosen. The blackbody furnace ISOTECH R970 is employed, whose effective emissivity is higher than 0.995 with the reference temperature ranging from 423 K to 1473 K. As shown in Fig. 2, the cavity of the furnace with the diameter being 20 mm is removable, and a fixed point cell can be put in its place to calibrate the temperature measuring equipment. The cavity inside the fixed point cell is 10 mm in diameter by 65 mm deep to the tip of a 120° cone. The temperature of the furnace is set on a controller, while the independent indicator indicates the actual radiance temperature using a high performance type R thermometer.

2.2. Sample heating system

The self-designed sample heating system is mainly composed of a cast iron plate heater and a temperature control system. As shown in Fig. 3 the electric heater of resistance wire is spirally inserted in the cast iron plate. The specimen inside the chamber is heated by the iron plate heater. To minimize the heat loss and shield the noise from the surrounding environment, the whole heater is highly insulated using aluminum silicate wool and enclosed in a stainless steel shell. The temperature control system is consisted with two main modules: a high resolution and precision digital PID (Shimaden SR23) controller and a high-performance power regulator. The temperatures of the samples are monitored by two high accuracy type K thermometers which are symmetrically-welded near the measuring point of the sample surface by using thermocouple welder. The output of one thermocouple as input signal is fed back to the digital PID controller and then calculated using intelligence PID control algorithm based on the expert system, and the output signal of another thermocouple is fed back to a temperature acquisition unit to monitor the sample temperature. The PID controller outputs a signal to control the power regulator (SHIMADEN PAC01A), letting the iron plate heater cast a suitable heating power. This design can greatly improve the temperature control precision and the heating efficiency. The temperature range is from 473 K up to 1273 K and the control precision is 0.1 K. Samples were processed into disc with the diameter being about 50 mm and the thickness being 2 mm. A disc aluminum silicate insulation board is mounted in front of the measuring sample to reduce the Size of Source Effect (SSE), which represents the relative contribution to the measure signal due to radiation outside the nominal measured area of the sample.

2.3. The optical system

The optical system of the apparatus consists of two parabolic mirrors, a motorized rotation stage, a grating monochromator and an optical table. To minimize the aberrations and reduce the loss of the radiation, two off-axis parabolic gold-coated mirrors are employed which can collimate a point light source or focus into a collimated beam. The effective focal length is 203.2 mm and the average reflectance is over 96% at a broadband range from 0.8 μm to 20 μm. The all-reflective design eliminates phase delays and absorption loss introduced by transmissive optics. The off-axis parabolic gold-coated mirror 3 is mounted on the motorized rotation stage, and the other off-axis parabolic mirror 4 is installed on optical table by an optical frame, the height of which could be adjusted precisely. The cast iron plate heater and the blackbody furnace are symmetrically-arranged on the two sides of off-axis