Determination of the effective emissivity distribution of a heated specimen using tandem acousto-optical tunable filter

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Abstract. We present the first experimental demonstration of a new imaging system for in-situ measurement of the two-dimensional distribution of the effective emissivity and temperature of a heated specimen. In this work, we use the model of a gray body, assuming that the emissivity is constant over the entire wavelength range from 600 to 800 nm. Data acquisition was done using the laser heating (LH) system developed at the STC UI RAS. The LH system allows us to reach extremely high temperatures up to 6000 K at high pressures. The main component of the system is an imaging tandem acousto-optical tunable filter synchronized with a video camera. The maximal error of the emissivity measurement of the tungsten sample was found to be 13%, whereas the maximal error of the temperature measurements did not exceed 2%. An influence of different factors on the error of the emissivity determination is also discussed.

1. Introduction
Spectral emissivity describes the ability of a material to emit radiation from a surface at a specific wavelength in relation to the radiation of a blackbody [1]. It is the basic material property characterizing radiation heat transfer [2]. Measurement of the emissivity at high temperatures is necessary for understanding many physical phenomena including thermal radiation heat transfer determination [3], processes in a diffusion flame [4], production of solar cells with a low emissivity [5], in thermal control of space crafts, highly efficient use of solar energy, energy insulation of buildings and saving, and so on.

In recent years, many studies have appeared related to the determination of emissivity [6]. Direct radiometric methods are based on a comparison of surface radiations of materials with calibration data (black body) at the same temperature, under the same geometric and spectral conditions [7, 8]. The experimental way to determine directional spectral emissivity $\varepsilon(\lambda, T)$ is directly based on the theoretical definition [2]. The experimental spectral emissivity can be obtained by two flux measurements: the sample directional spectral intensity $I_s(\lambda, T)$ and the blackbody spectral intensity $g(\lambda, T)$ at the same temperature, then the experimental directional spectral emissivity is given by a simple equation $\varepsilon(\lambda, T) = I_s(\lambda, T) / g(\lambda, T)$ [9]. This method can be easily applied if the temperature is the uniform over the surface of the specimen. However, if the specimen is heated by a laser beam, there is a strong temperature gradient over the heated...
area [10]. In this case, a distribution of the temperature \( T(x, y) \) and the emissivity \( \varepsilon(x, y) \) are determined by fitting the thermal radiation to Planck’s equation at for each isothermal area of the specimen surface [10]. In this study, we assume a small variation of emissivity \( \varepsilon_O \) over the spectral tuning range and the temperature range of the heated specimen. To date, the two-color method is one of the most popular methods for measuring temperature [11].

A modification of this method, the four-color method, was used to measure the temperature distribution in high-pressure cells in samples heated by a high-power laser [12]. Unfortunately, the use of this method to study the distribution of the emissivity in the heating region was not successful; the authors do not give the emissivity value, only relative values. [13]. One of the main drawbacks of the four-color measurement method is the small number of points (four) for obtaining two parameters (temperature and emissivity) from data for measuring the thermal radiation of a heated sample. To overcome this deficiency, we proposed using a video spectrometric method based on recording and processing images in narrow spectral intervals.

The purpose of this study is to determine emissivity distributions in samples with relatively uniform heating (tungsten lamp) and under high temperature conditions using the multispectral processing of thermal images of a heated plate using the laser heating with a tandem acousto-optical tunable filter (LH-AOTF) system described elsewhere [15]. It is demonstrated that the proposed method allows us to measure the emissivity of the tungsten with an error of 13% at the temperature of 2300 K.

2. Method

Traditionally, the calculation of temperature and emissivity is done by comparing the spectral data of the experiment with Planck's law (for details see [16, 17]):

\[
g(\lambda, T) = \frac{c_1}{\lambda^5 \exp(c_2/(\lambda T)) - 1},
\]

where \( \lambda \) is wavelength, \( T \) is the temperature, and \( c_1 \) and \( c_2 \) are first and second radiation constants \( (c_1 = 2\pi hc^2, c_2 = hc/k) \).

In our experimental set-up calibration is based on the imaging of a certified lamp at a temperature of 1700 K [18]. The lamp is placed at the position normally occupied by the sample place so that the spectral intensity \( I_{\text{optics}}(\lambda) \) (i.e., \( I(\lambda) \) at 1700 K) of the lamp is acquired through the optical pathways. To determine the spectral radiance of the heated specimen, \( I_{\text{corrected}}(\lambda) \), the following equation is used

\[
I_{\text{corrected}}(\lambda) = I_{\text{measured}}(\lambda)I_{\text{standart}}(\lambda)/I_{\text{optics}}(\lambda),
\]

where \( I_{\text{measured}}(\lambda) \) is the spectral intensity of the specimen during heating and \( I_{\text{standart}}(\lambda) \) is the spectral intensity of the calibration lamp.

The method of determining \( T \) from the experimentally determined \( I_{\text{corrected}}(\lambda) \) data is to find such values of \( T \) and \( \varepsilon \) at which the function \( [6, 19, 20] \),

\[
S(\varepsilon, T) = \sum_{i=1}^{N} [I(\lambda_i) - \varepsilon g(\lambda_i, T)]^2,
\]

where \( I \) is the spectral intensity from experiment; \( \varepsilon \) is the spectral emissivity of the sample; \( N \) is the number of wavelengths in experiment. This function has a minimum—by two-dimensional (2D) non-linear least square fitting. To decrease the effect of statistical error on the temperature determination, a more stable least-squares fitting procedure was introduced in [1]. It is based
on the fact that emissivity $\varepsilon$ in (1) is a linear parameter. We know that if the function $S(\varepsilon, T)$ has a minimum at $T_0$ and $\varepsilon_0$, then the following conditions should be satisfied:

$$\frac{\partial S}{\partial \varepsilon}|_{\varepsilon=\varepsilon_0, T=T_0} = 0$$

(4)

and

$$\frac{\partial S}{\partial T}|_{\varepsilon=\varepsilon_0, T=T_0} = 0.$$  

(5)

The first equation gives the value of $\varepsilon_0$:

$$\varepsilon_0 = \frac{\sum_{i=1}^{N} [I(\lambda_i)g(\lambda_i, T)]}{\sum_{i=1}^{N} [g^2(\lambda_i, T)]}.$$  

(6)

The second equation can be written as

$$\frac{\partial S}{\partial T} = -\frac{2c_2\varepsilon_0}{T^2} \sum_{i=1}^{N} \frac{\exp(c_2/(\lambda T))}{\lambda_i[\exp(c_2/(\lambda T)) - 1]} g(\lambda_i, T)[I(\lambda_i) - \varepsilon_0 g(\lambda_i, T)] = 0.$$  

(7)

To get the $T_0$ value we should use equation (7). The equation (7) was obtained in an analytical form and is transcendental equation; it can be also solved numerically. However, we will use another way to get $T_0$ [14]. Substituting (6) into equation (3) we obtain next expression:

$$S(T) = \sum_{i=1}^{N} \left[ I(\lambda_i) - \frac{\sum_{i=1}^{N} [I(\lambda_i)g(\lambda_i, T)]}{\sum_{i=1}^{N} [g^2(\lambda_i, T)]} g(\lambda_i, T) \right]^2.$$  

(8)

Therefore, the procedure described above reduces the problem of 2D non-linear least square fitting, equation (8), to one-dimensional (1D) non-linear least square fitting.

3. Set-up description
In the STC UI RAS, we developed a multifunctional system for measuring samples under high pressure and high temperature, equipped with an AOTF system and laser heating (LH) in high-pressure cells [21]. Figure 1 shows the part of the installation that was used to heat the tungsten lamp.
4. Results

The study was conducted using current heating (of 3.45 A) of the tungsten plate inside a bulb at wavelengths from 600 to 800 nm. Temperature and emissivity were measured at the area of 30×30 µm². We assume that in the mode of operation of the lamp, the temperature distribution is stationary, and due to the large thermal conductivity of tungsten and the non-edge position of the zone, the temperature gradients in the calibration region are small. However, the measured temperature field is not homogenous. There is a scattering of the measured temperature over the surface of lamp [figure 2(a)]: varies from 1710 to 1745 K.

The situation is different for the measurement of emissivity. As can be seen from figure 2(b) obtained values of the emissivity varies from 0.34–0.44, whereas the tabular value is 0.433 for 700 nm and 1700 K. [22] To obtain data for a temperature of 1700 K, the tabular values for 1600 and 1800 K were linearly approximated. Based on the data obtained, a value was found for the interval 1710–1745 K, it amounted to 0.432. The maximal error of the emissivity measurement a single point was found to be 20%.

5. Discussion

It is of interest to understand the nature of the error of the emissivity determination from the thermal radiation measurements. For simplicity, let us consider the Wien's expression for the thermal radiation and estimate influence of the error temperature measurement on the error of the emissivity determination. It is easy to obtain from Wien approximation:

$$\frac{d\varepsilon}{\varepsilon} = \frac{dI}{I} - \frac{c_2}{\lambda T} \frac{dT}{T}.$$  \hspace{1cm} (9)

The dependence is arranged so that a small error in temperature measurement leads to an increase in the measurement error of the emissivity. Substituting the values of our measurement errors $dI/I$ and $dT/T$ there, it was found that the coefficient of dependence of the emissivity error the $f(T)$ is approximately equal to 9, which correlates well with ours distribution results. At the same time, one can reduce this error by increasing the number of measurements and exploring the distribution over large areas.

Temperature variations from 1710 to 1745 K indicates that the accuracy of the method do not exceed ±20 K (1.2%). The scatter of the determined emissivity was about 20% that is more
than sixteen times higher of the dispersion of measured temperature. Our method assumes that the measurement error at the edges of the investigated region can be really high, but knowledge of the all distribution of temperature and emissivity in this region can significantly reduce this error. Thus, the expected value of the tungsten plate temperature at this current was 1726 K, and the measurement error at the point reaches 2%, while the average temperature at the site was 1736 K, which is much closer to the actual data and constitutes an error of only 0.6%. The similar tendency should be observed in the case of effective emissivity, the average value of which in the area under study was 0.37 ± 0.01, and the final error of the expected value was 13%.

6. Conclusion
The multispectral processing of thermal images of a heated plate using the laser heating with a tandem acousto-optical tunable filter system allows to determine emissivity distributions and measure the emissivity of the tungsten with an error of 13% at the temperature of 2300 K.

Acknowledgments
The present work is performed with the use of the Unique Scientific Instrument “Laser heating at diamond anvil cell” [http://ckprf.ru/usu/507563/].

References
[1] Honnerova P, Martan J and Honner M 2017 Appl. Therm. Eng. 124 261
[2] Siegel R and Howell J R 1992 Thermal Radiation Heat Transfer (Bristol: Taylor and Francis)
[3] Howell J R, Siegel R and Menguc M P 2010 Thermal Radiation Heat Transfer (CRC Press)
[4] Liu H W, Zheng S, Zhou H C and Qi C B 2016 Meas. Sci. Technol 27 10
[5] Jyothi J, Soum-Glaude A, Nagaraja H S and Barshilia H C 2017 Sol. Energy Mater. Sol. Cells 171 123
[6] Zhang Z M, Tsai B K and Machin G 2010 Radiometric Temperature Measurements I. Fundamentals 42 12
[7] Guo Y M, Pang S J, Luo Z J, Shuai Y, Tan H P and Qi H 2019 Int. J. Thermophys. 40 12
[8] Honner M and Honnerova P 2015 Appl. Opt. 54 669
[9] Rozenbaum O, Meneses D D, Auger Y, Chermanne S and Echegut P 1999 Rev. Sci. Instrum. 70 4020
[10] Bykov A A, Kutzu I B, Zinin P V, Machikhin A S, Troyan I A, Bulatov K M, Batshev V I, Mantrova Y V, Gaponov M I, Prakapenka V B and Sharma S K 2018 J. Phys.: Conf. Ser. 946 012085
[11] Pujana J, del Campo L, Perez-Saez R B, Tello M J, Gallego I and Arrazola P J 2007 Meas. Sci. Technol. 18 3409
[12] Campbell A J 2008 Rev. Sci. Instrum. 79 015108
[13] Du Z X, Amulele G, Benedetti L R and Lee K K 2013 Rev. Sci. Instrum. 84 9
[14] Zinin P V, Machikhin A S, Troyan I A, Bulatov K M, Bykov A A, Mantrova Y V, Batshev V I, Gaponov M I, Kutzu I B, Raschenko S V, Prakapenka V B and Sharma S K 2019 High Pres. Res. 39 131–49
[15] Bulatov K M, Mantrova Y V, Bykov A A, Gaponov M I, Zinin P V, Machikhin A S, Troyan I A, Batshev V I and Kutzu I B 2017 Computer Optics 41 864
[16] Heinz D L, Sweeney J S and Miller P 1991 Rev. Sci. Instrum. 62 1568
[17] Ribaud G 1931 Traite De Pyrometrie Optique (Paris: Ed, De La Revue)
[18] Machikhin A S and Batshev 2014 Inpress. Exp. Tech. 57 736
[19] Pletnichenko V G, Pyrkov Y N and Svet D Y 1999 High Press. Res. 37 444
[20] Rusin S P 2018 Thermophysics and Aeromechanics 25 539
[21] Machikhin A S, Zinin P V, Shurygin A V and Khokhlov D D 2016 Opt. Lett. 41 901
[22] Latyev I N, Petrov V A, Chekhov V Ya et al 1974 Radiative Properties of Solid Materials: A Handbook (Moscow: Energy)