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Research Paper

Uncertainty determination in high-temperature spectral emissivity measurement method of coatings

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HIGHLIGHTS

- Analysis of uncertainty of emissivity measurement method for thick coatings.
- Detailed identification of sources of uncertainty.
- Precision and applicability of the method identified.
- Original analysis approach can be beneficial to other emissivity measurement systems.

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ABSTRACT

The paper deals with uncertainty analyses of the new laboratory method for the measurement of spectral emissivity of high-temperature coatings. These coatings are intended to increase heat transfer in various industrial applications. The experimental set-up of the method is shortly introduced. The method is innovative in the application of scanning laser heating and in the coating surface temperature measurement using an infrared camera with a reference coating. Methods for total and partial uncertainty evaluation are described. As the uncertainty is always related to individual sample being measured, the DupliColor 800 °C paint (MOTIP Dupli Ltd.) is used as an example to introduce the results. Except the absorption bands the uncertainty is below 4% with coverage factor $k = 2$. Uncertainty spectral and temperature dependences are analyzed. Contribution of individual uncertainty sources as measured sample signal, measured laboratory blackbody signal, sample surface temperature, laboratory blackbody temperature, surroundings temperature, blackbody effective emissivity and surroundings emissivity and their subcomponents are discussed.

1. Introduction

Spectral emissivity describes the ability of material surface to emit radiation on a certain wavelength in relation to the radiation of a blackbody. It is the basic material property characterizing radiation heat transfer. The emissivity influence of processes and efficiency of high-temperature energy conversion devices is substantial. It concerns research of furnaces [1–3], heat exchangers [4,5], combustors [6], solar heat collectors [7], thermal energy storage [8], electric heaters [9], etc.

The research of applications of various materials in these devices brings about requirements for the development of laboratory methods for emissivity analyses to measure temperature and wavelength dependences. The spectral emissivity radiometric measurement methods were developed in various laboratory arrangements [10,11]. The methods differ in the applied reference sources of radiation, systems of sample clamping and heating, detection systems, methods for the determination of surface temperature, and procedures for emissivity evaluation. Emissivity spectral distribution together with the uncertainty estimation is the required output of the methods. Therefore uncertainty analyses and discussions on error sources are usually published side by the introduction of the newly developed emissivity measurement method or by its application.

Theoretically the problems of uncertainty determination concerning the emissivity measurement are discussed in [12]. The influences of surrounding/sample area ratio, surroundings emissivity, dependences on wavelength, sample surface temperature or surroundings temperature are analyzed in this paper. On contrary the published papers [13–19] introduce the experimental set-up and show uncertainty evaluations in relation to the specific method arrangement.

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Nomenclature

L	radiance
R	response function
T	temperature
V	spectrometer signal
X	individual source
Y	sub-component
Greek symbols	
Δ	difference
ε	emissivity
λ	wavelength
μ	absolute uncertainty
υ	wave number
ξ	relative uncertainty

Subscripts or superscripts	
$\wedge$	effective value
0	surroundings
1	lower value
2	higher value
B	blackbody
i	summing index of individual sources
j	summing index of sub-components
λ	spectral dependence
max	maximum
ref	reference
S	sample
t	time dependence

A new experimental set-up for the spectral emissivity high-temperature analyses has been developed at the New Technologies Research Centre at the University of West Bohemia in Pilsen [20]. The method is intended to measure thick opaque coating samples; however bulk metallic or ceramic samples can be analyzed as well. The method is innovative in the application of scanning laser heating [21] and in the coating surface temperature measurement using an infrared camera with a reference coating. Advantages of the heating method include the possibility to uniformly heat various samples concerning their magnitude and shape and the high heating rate on the required temperature level.

The advantages of the applied surface temperature measurement technique are the ability to consider temperature drop on the analyzed coating, the ability to monitor the temperature field of the sample and the non-contact principle without the installation and calibration of contact sensors. This paper is dealing with in-depth uncertainty determination concerning the method.

Some of the uncertainty aspects have been already mentioned in the paper [20] however very briefly. Our motivation is to introduce details throughout this paper that could be available to the heat transfer community and to the readers of our further research papers with applications of the emissivity measurement method and with results of analyses of various high-temperature materials for industrial applications. Therefore the influence of the most important parameters as the measured signals of the sample and laboratory blackbody, temperatures of the sample surface, blackbody and surroundings and emissivity of blackbody and surroundings is introduced in this paper. Results are shown in the form of spectral and temperature uncertainty dependences. The contribution of individual sources of uncertainty and their sub-components to the overall uncertainty is analyzed.

2. Experimental system and emissivity evaluation

The experimental system for spectral emissivity measurement uses a direct method of comparison of radiation fluxes from the sample and reference blackbody at the same temperature. The system consists of a FTIR spectrometer, heating laser, sample, reference blackbody, infrared camera, optical apertures, shutter, pointing lasers, rotary mirror and cover box [20]. The radiation sources are the heated sample and reference high temperature blackbody. The rotary mirror chooses the source of radiation. The spectrometer is used for detection of radiation and spectral resolution. The optical apertures define the spot of emissivity measurement on sample. The infrared camera precisely measures temperature on the surface of the measured coating. The spectrometer uses KBr beam splitter and temperature stabilized DTGS detector. The detected spectral range is 1.38–26 μm.

The opaque sample is heated by a 400 W continuous fiber laser with scan head. The scan head directs the laser beam on predefined paths on the back side of the sample in order to produce homogeneous temperature distribution on the front side [21]. The laser heating enables fast heating and temperature stabilization on different temperature levels and also measurement of samples with different size and shape. The temperature range of the system is 250–1000 °C.

The sample temperature measurement by the IR camera uses a reference coating deposited on a half of the sample over the measured coating [20,22]. The emissivity of the reference coating is once precisely calibrated with the infrared camera using a thermocouple under the coating in order to determine temperature on the surface of the measured coating. Further measurements are done without contact. The sample temperature homogeneity enables supposition of the same temperature in two symmetrical positions on the sample: the spot for temperature measurement by infrared camera and the spot for emissivity measurement by spectrometer.

The normal spectral emissivity of the measured coating $\varepsilon_{\lambda,\, n}$ (λ, T) is calculated according to [20]

$$\varepsilon_{\lambda,n}(\lambda,T)=\frac{V_{\lambda}^{S}(\lambda,T^{S})-V_{\lambda}^{B1}(\lambda,T^{B1})}{V_{\lambda}^{B2}(\lambda,T^{B2})-V_{\lambda}^{B1}(\lambda,T^{B1})}\cdot\frac{\hat{\varepsilon}^{B}L_{\lambda}^{B2}(\lambda,T^{B2})-\hat{\varepsilon}^{B}L_{\lambda}^{B1}(\lambda,T^{B1})}{L_{\lambda}^{B}(\lambda,T^{S})-\varepsilon^{0}L_{\lambda}^{B}(\lambda,T^{0})}+\frac{\hat{\varepsilon}^{B}L_{\lambda}^{B1}(\lambda,T^{B1})-\varepsilon^{0}L_{\lambda}^{B}(\lambda,T^{0})}{L_{\lambda}^{B}(\lambda,T^{S})-\varepsilon^{0}L_{\lambda}^{B}(\lambda,T^{0})}, \tag{1}$$

where λ is wavelength, T temperature, V spectrometer signal, L_{λ}^{B} blackbody spectral radiance, ε emissivity, $\hat{\varepsilon}^{B}$ blackbody effective emissivity, indexes $B1$ and $B2$ mean blackbody at lower and higher temperatures, index S means investigated sample and index 0 means surroundings. The spectrometer signals are obtained by measurement of radiation of sample at sample temperature and blackbody at higher and lower temperatures around the sample temperature. The blackbody spectral radiances are computed according to the Planck's law at specified temperatures.

3. Method for total uncertainty evaluation

Spectral dependence of normal emissivity of each measured coating is loaded by an uncertainty that coming out from the used measuring apparatus, and the chosen method of measurement and evaluation of emissivity. In this method, the total uncertainty of