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Experimental mathematical model as a generalization of sensitivity analysis of high temperature spectral emissivity measurement method

Petra Honnerová *, Zdeněk Veselý *, Milan Honner

New Technologies Research Centre (NTC), University of West Bohemia, Univerzitní 8, 306 14 Pilsen, Czech Republic

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ABSTRACT

The development of an experimental mathematical model describing temperature state of the sample during high temperature spectral emissivity measurement is introduced. Dimensional analysis of the measurement process gives the physical dimensionless quantities and sensitivity analysis of the measurement process provides the large set of performed model experiments. Evaluated experimental mathematical models are presented including their accordance with model experiments. Established equations are generalization of sensitivity analysis of high temperature spectral emissivity measurement method and can be used for computation of spectral emissivity total uncertainty.

1. Introduction

Emissivity is a physical quantity that defines how much infrared radiation is emitted by a real surface in comparison to an ideal blackbody. Direct [1–4] or indirect [1,5–7] methods are utilized for the emissivity measurement. A temperature dependence of spectral emissivity is usually measured by the direct radiometric methods [8–11]. The direct ones are based on the comparison of sample radiation to a reference body radiation at the same temperature, under similar geometrical and spectral conditions [12]. The emissivity measurements accuracy by direct radiometric methods is mainly affected by the uncertainty on the measurement of the real sample surface temperature. For example, the emissivity uncertainty of approximately 1% is the results of an uncertainty in the sample surface temperature measurement of 0.5 °C at the temperature 100 °C [13].

High temperature spectral emissivity measurement method [14] is primarily applied for the normal spectral emissivity measurement of high-temperature coating with different thickness up to temperature 1000 °C. The application of contact methods based on the surface temperature determination from temperatures measured inside the sample is limited. Measurement of surface temperature by contact method provided by thermocouple measurement in certain depth from surface does not include temperature drop across the thickness of measured coating, thus a high emissivity uncertainty is obtained. The difficulty in surface temperature measurement of coatings is solved with the help of an infrared camera system and a reference coating deposited on a part of the measured sample surface. On the other side, the reference coating influences the sample radiation behavior and sample surface temperature distribution [15,16].

The computer model giving the temperature distribution of the sample in a steady state is employed in the sensitivity analysis of high temperature spectral emissivity measurement method. Temperature distribution in the sample during emissivity measurement is evaluated for a considerable number of prescribed sample temperatures, emissivities of measured coating and thicknesses of reference and measured coatings [17]. These sample temperature distributions are outputs of the sensitivity analysis.

Experimental mathematical model is used to summarize and generalize the results from sensitivity analysis. Experimental mathematical models (experimental models) are created using the mathematical apparatus called dimensional analysis and the number of experiments performed. Experimental models are used to describe physical processes in the cases where utilization of asymptotic mathematical models (equations of mathematical physics) are not possible because they are not known or it is too complicated to use them. Complicated mathematical models need a lot more time to be processed than simple equations called

* Corresponding authors.
E-mail addresses: petrahon@ntc.zcu.cz (P. Honnerová), zvesely@ntc.zcu.cz (Z. Veselý), honner@ntc.zcu.cz (M. Honner).

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Nomenclature

a, b, c, d, e	unknown parameters of experimental mathematical model
A	dimensionless heat transfer coefficient
Bi	Biot number
d	thickness
D	dimensionless thickness
Ki	Kirpitchev number
L	reference length
n	number of computer model experiments
q	heat flux
Q	dimensionless heat flux
r	sample diameter
R	dimensionless sample diameter
R^2	determination index
Sf	Stefan number
T	temperature
y	quantity from computer model
$\hat{y}$	quantity from the experimental mathematical model
$\bar{y}$	average value of the quantity

Greek symbols

α	heat transfer coefficient
Δ	difference
ε	emissivity
θ	dimensionless temperature
λ	thermal conductivity
Λ	dimensionless thermal conductivity
σ_0	Stefan–Boltzmann constant

Subscripts

ave	average
A	spot A
B	spot B
C	spot C
e	external
i	summing index
mc	measured coating
rc	reference coating
rc/mc	interface of reference and measured coating
ref	reference
s	substrate
S	surface
1, ..., 7	resolving index

experimental models. Experimental models are only approximate expression of precise results, but in many cases it is sufficient.

Using dimensional analysis [18–25] of high temperature spectral emissivity measurement method, dimensionless similarity quantities for measurement method description are obtained. These dimensionless quantities and a large number of computer model results for optional parameters of the sample and measurement method are inputs to the procedure for experimental mathematical model evaluation. As a result, the experimental mathematical model describing dependence of temperature difference of average temperature on the surface of measured coating and average temperature at the interface of reference and measured coatings is realized. The temperature difference from the experimental mathematical model can be used for more precise determination of measured coating surface temperature and for uncertainty evaluation of high temperature spectral emissivity measurement method.

2. Emissivity measurement method

2.1. High temperature emissivity measurement method

High temperature emissivity measurement method is briefly introduced in the section. A more detailed description of the method can be found in [14,26].

The method is based on the comparison of radiation of a blackbody and of the sample surface that are positioned opposite to each other. The radiation is collected by a rotary parabolic mirror situated halfway between the radiation sources. The spectral detection of radiation is performed by a FTIR spectrometer (Nicolet 6700). The optical path of radiation is covered by an optical box. The sample is clamped to a ceramic insulation and is heated to the required temperature by a fiber laser with a scanning head. The sample surface temperature is measured noncontactly by an infrared camera (FLIR A320) with wavelength range from 7.5 μm to 13 μm. The temperature dependence of normal spectral emissivity is evaluated in the wavelength range from 1.38 μm to 26 μm. The samples can be heated up to 1000 °C.

The applied noncontact surface temperature measurement requires the knowledge of effective emissivity of the measured surface for the infrared camera and viewing angle. The problem is solved by the deposition of the reference coating (ZYP Coating Cr_2O_3) with known effective emissivity on the half of the measured

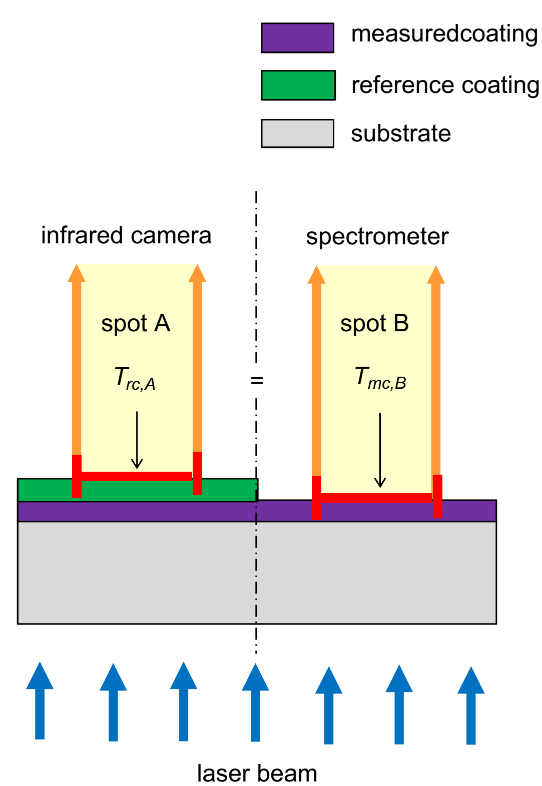

Fig. 1. Temperature and emission measurement positions in the emissivity measurement method (spot A is on reference coating, spot B is on measured coating) and temperature evaluation area in the model of the heat transfer in the sample.