DETERMINATION OF INDICATRICES OF SURFACE BRIGHTNESS OF MATERIALS AND COATINGS FROM MEASUREMENTS ON THEIR SPHERICAL SPECIMENS

M. V. Tantashev and G. K. Kholopov

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The main principles of a measurement procedure are given and its implementation with the aid of an IR-imager AGA-780 is shown.

One of the basic characteristics describing the radiation properties of light-diffusing materials and coatings is the spatial reflection indicatrix. When a test specimen of the material is exposed to illumination from some fixed directions, the indicatrices of its surface reflection characterize a change in the intensity of the reflected flux in dependence on the angles determining the directions of reflection. For the material and coatings with the isotropic surfaces, the direction of illumination is characterized only by the zenith angle θ_{il} counted off the normal to the surface in the plane of light incidence (this plane comprises the direction of light incidence and the normal to the specimen surface) while the direction of reflection is determined by two angles, namely, by the zenith angle θ_{ob} between the chosen direction of reflection and the mentioned normal and by the azimuthal angle φ_{ob} between the planes of incidence and reflection (the latter includes the direction of reflection and the normal to the specimen surface). Thus, devices to measure reflection indicatrices, usually called goniophotometers, must have, with respect to the number of arguments of the measured function, at least three degrees of freedom allowing measurement relatively each other of mutual angular positions of goniophotometer elements: a illuminator, a specimen, and a photometer (a device measuring the luminous intensity in given directions). The three degrees of freedom in the traditional goniophotometers are realized through different kinematic schemes using a flat specimen. Thus, in [1] the classical scheme is implemented with the angles of illumination set at discrete values $0 \leq \theta_{il} < 90°$ in the plane of incidence and a photometer subsequently displaced within the semispherical space above the illuminated surface of a specimen fixed in position by the azimuthal ($0 \leq \varphi_{ob} < 360°$) and zenith ($0 \leq \theta_{ob} < 90°$) angles of reflection.

According to the measurement method realized in the device [2], the illuminator is fixed, while a specimen is set at the discrete values of angles θ_{il} towards an optical axis of the illuminator on a rotating axis parallel to it. When the specimen turns around this axis, the angle of light incidence does not change. A photometer displaces about the specimen's center in one of the planes containing the optical axis of the illuminator. Thus, moving along both sides from a test specimen in some trajectory determined by the ratio of angular velocities of turning the specimen and the photometer, the latter accomplishes photometric measurement of an illuminated side of the specimen within the limits of the semispherical solid angle above it. Then the angular coordinates of the device elements, determining the positions of the specimen and the photometer, are transformed into coordinates θ_{il}, φ_{ob} and the measured brightness or luminous intensity of the specimen are related to the system of coordinates (θ_{il}, θ_{ob}, φ_{ob}).

The method of measuring the indicatrices of brightness [3] envisages a change in the position of a specimen with respect to two degrees of freedom (angles β and γ) relatively a illuminator and a photometer, the optical axes of which converging at the center of the specimen are set at the angles of scattering α whose values are prescribed discretely within $0 \leq \alpha < 180°$. Here, in the plane containing the optical axes of the ligher and the photometer, the angles β change from zero, corresponding to the direction of the normal to the specimen, coinciding with the bisectrix of the angle α, to the values of $\beta = \pm (90° - \alpha/2)$, while the angles γ in the plane perpendicular to it vary within $-90 < \gamma < 90°$. To represent the indicatrices of brightness in the traditional form, the system of angular coordinates (α, β, γ) is transformed into the system (θ_{il}, θ_{ob}, φ_{ob}) and a bulk of the measured brightness L (α, β, γ) are computer-converted into a bulk of L (θ_{il}, θ_{ob}, φ_{ob}) values.

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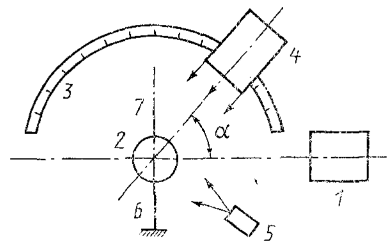


Fig. 1. Schematic of the device used to realize the measurement technique.

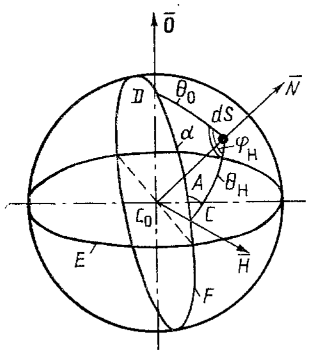
Below, the method is described to measure indicatrices of brightness of light-diffusing coatings applied to spherical, but not flat, substrates [4]. The main idea behind it lies in the fact that a sphere surface may be represented as a set of flat elements having an orientation in space which corresponds to the uniform, in all direction, density of distribution of normals to each of them. Such kind of a test specimen permits incorporating only the movable goniophotometer system, i.e. setting the discrete values [3] of angles between the optical axes of a illuminator and a photometer. Another two degrees of freedom are realized by photometer scanning of the specimen and element-by-element scanning photometrically the brightness field of a sphere image produced at its outlet. Scanning photometers may be designed following the operational principle of television and IR-image systems with linear registering tracts.

An essence of the method is as follows. A test coating is applied to a concave surface of a substrate which is made in the form of a sphere (or at least a hemisphere). The sphere is placed into a light beam produced by a colliminated illuminator. A scanning photometer creates the sphere image in the plane of its sensing element consisting of a set of elements, the number and dimensions of which are determined by the parameters of optical and photorecording systems of the photometer. In the frame obtained at the photometer outlet, determination is made of the center and radius of the sphere image as well as the axis of symmetry of the illuminated part of the sphere. On the obtained image is imposed the rectangular system of coordinates, the origin of which coincides with the center of two axes with the axis of symmetry of the illuminated part of the sphere. The brightness of each coating element on the illuminated sphere image is determined simultaneously with its linear coordinates in their imposed rectangular system. The angular coordinates of the illuminator and the photometer, as applied to each measure element of the coating, are determined by the values of these two linear coordinates and the angle formed by the optical axes of the illuminator and the photometer. llumination by a collimated beam within the section occupied by a sphere and sensitivity of the photometer within its field of observation containing the sphere must be constant.

The device used to approbate this method is shown schematically in Fig. 1. It consists of photometer 1 which is fixed in position with its optical axis running through the center of spherical specimen (a sphere) 2. Rigid guide 3 in form of a flat arc mounts illuminator 4. It moves along arc 3 changing the scattering angle α from 10 to 170° in such a way that its optical axis always passes through the center of sphere 2 and is positioned in one plane which also contains the optical axis of photometer 1. As auxiliary elements useful for determining the parameters of the spherical specimen image, use has been made of supplementary illuminator 5 illuminating sphere 2 to ensure entire illumination of its side facing the photometer together with its main collimated illuminator 4, straight rigid rod-holder 6 whose axis runs through the sphere's center and is in the same plane as the optical axes of illuminator 4 and photometer 4 as well as separable thin rod 7 being an extension of rod-holder 7 from the opposite sphere side and strictly aligned with the holder.

A short-wave (1.8-5.5 μm) channel of an IR-imager AGA-780 (ACEMA, Sweden) certified in units of power brightness for sensitivity was used as photometer 1.* To each element of the field of vision of the device was given its coordinates corresponding to the number of a row, to which it belongs, X and the ordinal number of an element in the row Y. Linear scales of the coordinate axes and dimensions of the elements along these axes were the same. The image of 80 mm diameter sphere 2 with a uniform test coating layer took up more than a half of the field of vision of the device and was observed on the screen of a picture monitor (PM). Illuminator 4, designed on the basis of a quartz lens and a halogen incandescent lamp, produced a 120 mm diameter collimated beam of radiation. Scanning photometrically the sphere was performed with and without illumination by illuminator 4. A bulk of the produced data for both cases was incorporated into a computer and then calculated element-by-element. Thus, the thermal radiation effect of the sphere and its environment on measurement results was ruled out.

*Setting the device scale for power brightness units, measuring and recording a bulk of data have been performed by A. V. Serebryakov.



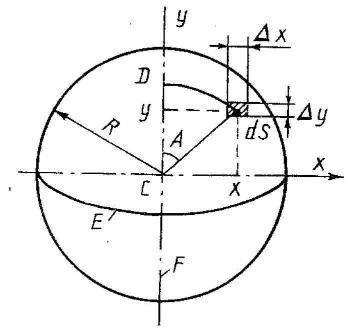


Fig. 2 Fig. 3

Fig. 2. Three-dimensional presentation of mutual angular positions on the sphere of unit vectors determining directions to the illuminator Ō, the photometer H̄, and the normal to the scanned photometrically element dS(N̄); the line E determines the boundary of the illuminated part of the sphere, the line F is the trace of cutting the sphere with the plane containing vectors Ō and H̄; the point C_{il} is the sphere center; C and D on the sphere surface are the nearest points to the photometer and the illuminator, respectively; A is the azimuthal angle formed by the planes containing the vectors Ō and H̄ and the vectors N̄ and $\theta_0 = \theta_{il}$; $\varphi_H = \varphi_{ob}$.

Fig. 3. Three-dimensional image of the sphere in the plane of sensing elements of the photometer with the coordinate system xCy imposed on it; the point C, the circle center of the sphere image; R, the image radius; Cy, the axis of symmetry of the illuminated part of the sphere coincides with a trace of the plane F; designations A, E, F, C, and D are the same as in Fig. 2.

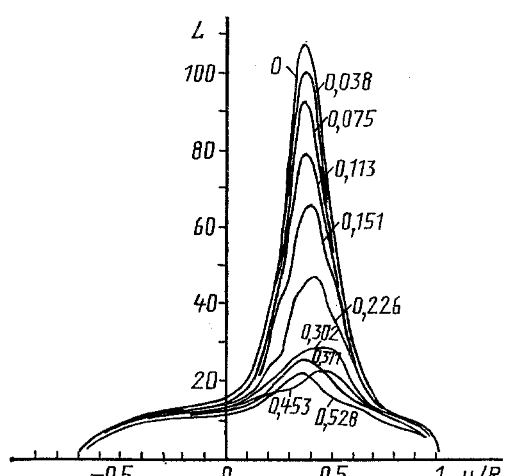


Fig. 4. Some measurement results (in relative units) corresponding to cross sections of the brightness field of the image of the sphere with the test reflecting coating obtained by an AGA-780 IR-imager.

With switched illuminators 4 and 5 displaced on the device mount, a straight line formed by rods 6 and 7 was adjusted strictly along the axis regarding the sphere image on the PM screen.

Then the coordinates of boundaries of the sphere image, i.e. the upper X_1, the lower X_2, the left Y_1, and the right Y_2 were determined, the coordinates of the circle center of the image $X_c = (X_1 + X_2)/2$ and $Y_c = (Y_1 + Y_2)/2$ and the image radius $R = (X_1 - X_2)/2 = (Y_1 - Y_2)/2$ were calculated. Using these results, we introduced a new system of coordinates xCy by parallel translation of axes without changing their scales.

After switching off illuminator 5 and removing rod 7, we recorded the brightness field of the image of that part of the sphere which was illuminated by illuminator 4. The brightness of each element of the image dS determined by the linear coordinates (x,y) was matched up with the angular coordinates (θ_{il}, θ_{ob}, φ_{ob}) characterizing this element which, according to the notation in Figs. 2 and 3, are expressed as follows:

$$\sin \theta_{ob} = (x^2 + y^2)^{1/2}/R, \tag{1}$$

$$\cos \theta_{il} = \cos \alpha \cos \theta_{ob} + (y/R) \sin \alpha, \tag{2}$$

$$\cos \varphi_{ob} = (\cos \alpha - \cos \theta_{il} \cos \theta_{ob})/(\sin \theta_{il} \sin \theta_{ob}). \tag{3}$$

The illuminated part of the sphere (the illuminated hemisphere) has sections, the whole set of illumination angles θ_{il} of which ranges from 0 to 90°. Some of these sections are visualized by the photometer at different angles θ_{ob} and φ_{ob}. All these values are interrelated according to (1) through (3). Thus, scanning photometrically the sphere image at each angle α yields a lot of results corresponding to certain regions of the angles θ_{il}, θ_{ob} and φ_{ob}. An increase of the number of the scattering angles within $0 \leq \alpha \leq 180^0$ entails extension thus all possible values of the illumination and observation angles and decrease a mean interval between the neighboring points for each of three angular coordinates.

Figure 4 is an example of photometric measurement of one of the images of the sphere having an "aluminium powder" coating at $\alpha = 45°$ Brightness distributions are shown in relative power units with respect to sections of the sphere image corresponding to constant values of the coordinate x (see Fig. 3). The figures at the curves indicate the x/R values appropriate for them. For the sake of simplicity the sampling of data at $x \geq 0$ is far from being complete. Analogous results have been obtained at other scattering angles: from $\alpha = 15°$ to $\alpha = 150°$ with a step of 15°. Processing the bulks of data analogous to Fig. 4 by using (1)-(3) has allowed determination of the brightness indicatrices L(θ_{il}, θ_{ob}, φ_{ob}) of the test unglossy coating in the range $\theta_{ob} \leq 83°$ (for larger angles the results are not sufficiently reliable because of appreciable deterioration of angular resolution).

Thus evaluation of the proposed measurement method has demonstrated its simple realization with the aid of a scanning photometer (or a radiometer) producing multielement representation of a sphere with a test coating and allowing the analysis of a brightness field of the image recorded by it.

To sum up, a spherical shape of a substrate is not the only possible condition for implementing the method under discussion. If some directions of illumination or observation are preferable, the substrates of other curvet form may be used whose surfaces are sufficiently accurately reproduced and mathematically described. The method may be modified to be applied for measuring the brightness indicatrices of extended surfaces, for instance, the smooth Earth places illuminated by the Sun. For this purpose, all the surface may be element-by-element scanned photometrically with the aid of its image in a specular (hemi) sphere placed above it.

NOTATION

$\bar{N}$, $\bar{O}$, $\bar{H}$, unit vectors determining: $\bar{N}$, position of the normal to a test element dS of a spherical surface (and a plane tangential to it), $\bar{O}$, direction from the element to the illuminator; $\bar{H}$, direction from the element to the photometer; X, Y and x, y, linear coordinates of the element dS on the sphere image; R, radius of the sphere image; L, brightness; α, angle between optical axes of the illuminator determining the specimen positions in space with its turning along two mutually perpendicular axes; θ, φ, angles in the system of spherical coordinates related with the element dS; θ, zenith angle counted off the normal; φ, azimuthal angle counted off the plane of incidence. Indices: il, illumination (an illuminator); ob, observation (a photometer); c, center of the sphere image.

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IDENTIFICATION OF CONTACT THERMAL RESISTANCES IN NUCLEAR REACTOR FUEL ELEMENTS. 2. PROCESSING OF EXPERIMENTAL RESULTS

E. A. Artyukhin, A. V. Nenarokomov, A. P. Tryanin,
S. A. Utenkov, and V. V. Yakovlev

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The results of experimental computational determination of contact thermal resistances (CTR) between the heat-evolving cores and jackets of nuclear fuel elements are presented. The dependence of the CTR magnitude on the linear heat loading of the fuel element is analyzed.

The present paper considers the problems of practical utilization of the parametric identification method suggested in [1]. Experiments were conducted with fuel elements of the water-moderated water-cooled power reactor-440 type (WMWCPR-440) in a medium reactor (MR) [2]. An experimental fuel assembly (FA) consisted of 18 elements arranged in two rows (Fig. 1); it was cooled with water under a pressure of 160 MPa. Fuel elements R1-R6 were equipped with in-fuel internal reactor (IR) thermocouples located in the central hole of the fuel element core in the axial cross section corresponding to the zone of maximum energy release. Major characteristics of the fuel elements are listed in Table 1.

Volumetric distribution of energy release in the FA was determined with the aid of axial and azimuthal arrays of neutron flux sensors [rhodium direct charge detectors (DCDs)]. The heat-transfer agent pressure and temperature were measured at the FA inlet. The heating of the heat-transfer agent over the working section of the FA was measured by a differential chromel–alumel thermocouple, the volumetric heat-transfer agent flow rate was determined with the aid of an orifice plate. An instantaneous energy release in thermometric fuel elements was controlled by a rhodium DCD equipped with an amplifier-corrector BNTK-1A. The rhodium DCD readings are described by the following system of equations

$$J(\tau) = lk\lambda_1 N_1(\tau) + \alpha l_k (\sigma_1 + \sigma_2) n\Phi(\tau),$$
$$\frac{dN_1(\tau)}{d\tau} = \lambda_1 N_1(\tau) + \lambda_2 N_2(\tau) + \sigma_1 n\Phi(\tau), \quad \frac{dN_2(\tau)}{d\tau} = \lambda_2 N_2(\tau) + \sigma_2 n\Phi(\tau), \tag{1}$$

where l, k, n are constants; $N_1(\tau)$ and $N_2(\tau)$ are the concentrations of isotopes Rh^{104} and Rh^{104m}; $\Phi(\tau)$ is the instantaneous neutron flux; α is the instantaneous signal component resulting from the nuclear Compton effect (for the DCDs used in the present experiment $\alpha = 8\%$); $\sigma_1 = 139$B and $\sigma_2 = 11$B are the neutron-capture cross sections for Rh^{104} and Rh^{104m}; $J(\tau)$ is the DCD signal (from 0 to 1-2 μA).

By applying the analog method, the BNTK-1A amplifier-corrector solves the system of equations (1) converting the DCD signal $J(\tau)$ into a normalized signal E^{im} (0-5 V or 0-10 V) associated with the power characteristics of FA and of separate fuel elements by the following relationships

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