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MEASUREMENT OF THE TEMPERATURE OF A SURFACE IRRADIATED BY CONCENTRATED LIGHT

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A new method is proposed for determining the thermodynamic temperature of a surface irradiated by concentrated light.

INTRODUCTION

The development of studies of interaction between concentrated light radiation and materials requires reliable measurements of the parameters of the process. The basic experimental parameter characterizing the interaction process is the temperature of the irradiated surface. However measurement of the thermodynamic temperature of material surfaces during action of concentrated light radiation involves significant methodological difficulties related to pyrometry of an open surface, complicated by the need to eliminate powerful reflected light fluxes. Thus it was only in 1979 that M. Bober (West Germany) developed a method for correct solution of the problem of measurement of the thermodynamic temperature of the diffusely reflecting surface of refractory materials subjected to high power laser radiation [1, 2]. Analysis of Soviet and foreign sources for the subsequent decade [3, 4] showed that the majority of researchers used Bober's method for measuring the temperature of the irradiated surface of various materials. It should be noted here that Bober's method is valid only for diffusely reflecting materials and is inapplicable to materials with specular and mixed reflection, which class includes the majority of modern technology materials actively used in intense light fluxes. The latter class includes the resonators of high power modern lasers with specular type reflection, composition thermal insulation materials with fiber and dispersed fillers, oxides with a mixed type reflection (although in the latter case powder metallurgy methods permit creation of parts with surfaces having close to diffuse reflection).

The present study will develop a method for measuring the thermodynamic temperature of a surface with arbitrary reflection indicatrix under the action of concentrated light.

MEASUREMENT METHOD

Pyrometry in the visible wavelength range is based on Wien's expression

$$E^0_{\lambda,T} = C_1\lambda^{-5}\exp\left(-\frac{C_2}{\lambda T}\right). \tag{1}$$

Using the concepts of brightness temperature and spectral emissivity, we write the equation

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$$E^0_{\lambda T_b} = \varepsilon_\lambda(\theta, \varphi, T)\, E^0_{\lambda T}, \qquad (2)$$

from which we obtain an equation relating the thermodynamic and brightness temperatures:

$$T^{-1} - T_b^{-1} = C_2^{-1}\lambda \ln \varepsilon_\lambda(\theta, \varphi, T). \qquad (3)$$

The main experimental difficulty in measuring the thermodynamic temperature of a surface heated by concentrated radiation is related to determining the directional spectral emissivity.

Since it is not always possible to model an ideal black body with intense heating from one side, to determine $\varepsilon_\lambda(\theta, \phi, T)$ we use the spectroreflectometric method of [5], unregulated application of which under conditions of exposure to concentrated light may lead to a number of methodic errors. Therefore, we will consider this method in detail.

If in a direction defined by polar θ and azimuthal ϕ angles there falls on an element of an opaque body a monochromatic radiation flux at wavelength λ, then according to the law of conservation of energy, the incident flux will equal the sum of the radiation fluxes absorbed and reflected. In dimensionless form this relation can be expressed as:

$$\alpha_\lambda(\theta, \varphi, T) + \rho_\lambda(\theta, \varphi, 2\pi, T) = 1. \qquad (4)$$

In transforming from spectral absorption capability to spectral emissivity we should note that only one formulation of Kirshhof's law transforms without limitations and remains valid in the absence of thermodynamic equilibrium: the directional spectral absorption capability $\alpha_\lambda(\theta, \phi, T)$ is equal to the directional spectral emissivity $\varepsilon_\lambda(\theta, \phi, T)$. We then obtain an expression for the spectroreflectometric method of determining emissivity:

$$\varepsilon_\lambda(\theta, \varphi, T) = 1 - \rho_\lambda(\theta, \varphi, 2\pi, T). \qquad (5)$$

Equation (5) is valid over the range of applicability of the hypothesis of local thermodynamic equilibrium and opaqueness of the specimen. Determination of emissivity under intense deviations from thermodynamic equilibrium, in particular, action of strong light fluxes, places increased demands on the conditions for satisfaction of Kirchhof's law and the conservation laws. Therefore before Bober's study methodical errors in determination of the irradiated surface temperature were introduced. To determine the directional hemispheric spectral reflection coefficient Bober used a variant of Taylor's relative method using an integrating sphere [2]. The theory of the method assumes the presence of an ideal diffusely reflecting surface (the integrating sphere) and reduces to determination of the luminosity of the sphere walls. However the real reflecting coating of the integrating sphere does not produce uniform wall luminosity and limits its application to materials with a diffuse type surface reflection. Therefore, for materials with mixed or mirror reflection Bober's method does not give the coefficient $\rho_\lambda(\theta, \phi, 2\pi, T)$.

We propose measurement of the directional hemispheric spectral reflection coefficient of the surface irradiated by concentrated light not by direct, but indirect experiment, determining the hemispherical directional spectral reflection coefficient $\rho_\lambda(2\pi, \theta, \phi, T)$ under conditions of diffuse specimen illumination

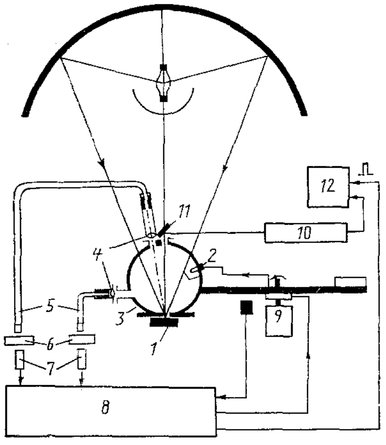

Fig. 1. Diagram of experimental arrangement.

$$\rho_\lambda(2\pi, \theta, \varphi, T) = \frac{L(2\pi, \theta, \varphi)\cos\theta\Delta\omega}{\pi L_0}, \quad (6)$$

where $\Delta\omega$ is the solid angle element within which the reflected radiation is recorded.

In this case (i.e., with diffuse specimen illumination), according to the reciprocity property [6], the hemispheric directional spectral reflection coefficient is equal to the directional hemispheric spectral reflection coefficient, where the observation direction in the first case is the same as the direction of radiation incidence in the second.

Indirect determination of the directional hemispheric spectral reflection coefficient is convenient in that it simplifies experimental method by eliminating the need to record all the radiation reflected into the hemisphere, and also because it makes possible study of surfaces with a complex indicatrix of reflection.

It should be noted at this point that in realizing measurements of the hemispherical directional reflection coefficient complications develop due to dependence on the solid angle of the recording system [Eq. (6)]. However, by using relative measurements one can eliminate that dependence and transform to determining the ratio of the brightnesses of the specimen and a reference, which under diffuse illumination conditions will equal the ratio of the hemispherical directional reflection coefficients of the specimen and reference.

METHOD FOR MEASUREMENT OF THERMODYNAMIC TEMPERATURE

As was already noted above, in measuring the thermodynamic temperature of a surface irradiated by concentrated radiation and having an arbitrary indicatrix of reflection, it is necessary to determine the brightness temperature and the hemispherical directional spectral coefficient $\rho_\lambda(2\pi, \theta, \phi, T)$, while to measure the brightness temperature T_b from the intrinsic radiation of the specimen, the powerful fluxes of reflected heating radiation must be eliminated.

The experimental arrangement which realizes this method for determining the true temperature of an irradiated surface with mixed type reflection is shown in Fig. 1.

The specimen under study 1 is placed at the focus of an elliptical mirror of an optical

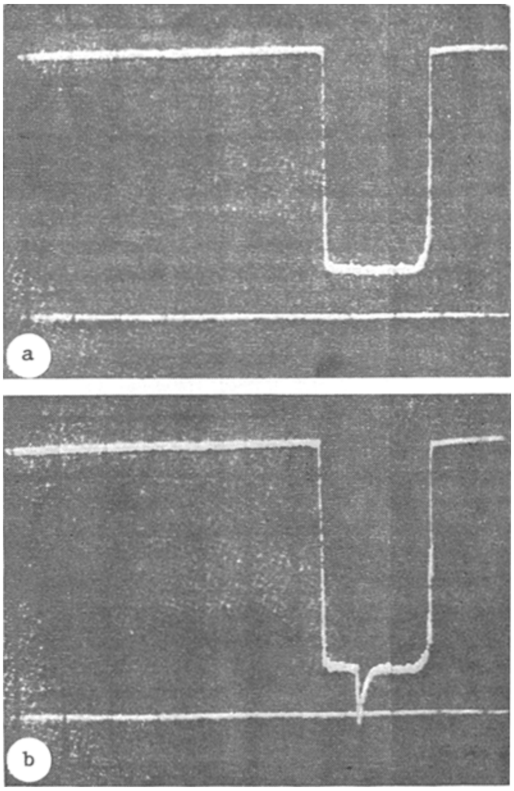

Fig. 2. Oscillograms of brightness pyrometer signals for Al_2O_3: a) without flash; b) with flash.

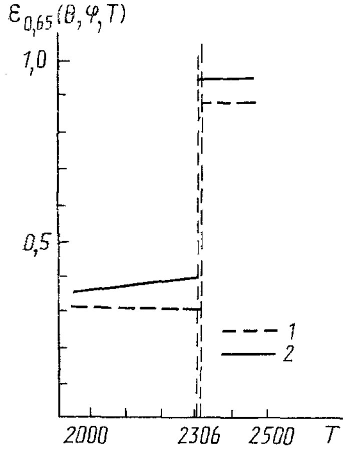

Fig. 3. Directional radiation coefficient $\varepsilon_{0.65}(\theta, \phi, T)$ vs temperature for Al_2O_3: 1, data of [1]' 2, present measurements, T, K

furnace which is the concentrated radiation source. The radiation of flash lamp 2, located on integrating sphere 3 is used to create diffuse illumination of the specimen. The inside of the integrating sphere was coated with a highly reflective $BaSO_4$-based material. Flux photometry is carried out through two channels – measurement and reference. The flash lamp radiation reflected from the specimen and the intrinsic thermal radiation of the specimen pass through the measurement channel optical system, consisting of objective lens 4, lightguide 5, and interference filter 6, and are then applied to photodetector 7, the output of which is fed to the control complex 8 based on an MS-2702 microcomputer. The optical system was aimed at the center of the specimen. The signal from the reference channel was used to monitor the power of the flash. The reference channel optical system was aimed at the inner wall of the sphere.

To measure the intrinsic radiation of the specimen the integrating sphere was set into rotation by electric motor 9 and briefly closed off the heating radiation. At the moment of cutoff the orifice in the lower part of the sphere was located above the center of the specimen.

The brightness temperature of the specimen was monitored by a high speed pyrometer 10, sighted on its surface by means of mirror 11, with readout to the screen of an S8-13 memory oscilloscope 12. The specimen had the form of a tablet 15 mm in diameter and 3 mm thick. The diameter of the area viewed was 1 mm.

The hemispherical directional reflection coefficient was measured in two stages. In the first stage the specimen under study was replaced by an MS-20 milk glass reference specimen ("white body"). The sphere was passed above the specimen twice. In the first passage the measurement and reference channel signals were measured with no flash (dark) – U^{ref}_{d}, U^{ref}_{rfl}; in the second passage signals were measured with a flash – U^{ref}, U^{ref}_{0}. The signal values were stored in the computer memory. In the second stage the specimen to be studied replaced the milk glass. The optical furnace was then used to heat it to a specified temperature. The sphere rotation motor was then turned on. In the first pass measurement and reference channel signals were measured with no flash: dark plus specimen radiation $U_d + U_s$, $U_{rfl} + U_{0s}$. In the second pass with flash the values U, U_0 were measured and stored in computer memory. The computation formula for calculating the hemispherical directional spectral reflection coefficient has the form:

$$\rho_\lambda(2\pi, \theta, \varphi, T) = \frac{U - (U_d + U_a)}{U_o - (U_{rfl} - U_{os})} \Bigg/ \frac{U^{ref} - U^{ref}_{d}}{U^{ref}_{o} - U^{ref}_{rfl}} \rho_{B,\lambda}(2\pi, \theta, \varphi). \quad (7)$$

A problem of special interest is the measurement of the fusion temperature of refractory oxides, since in such a phase transition the character of the indicatrix changes, with a predominantly diffuse type of reflection changing to predominantly specular.

Figure 2 shows oscillograms of signals from the brightness pyrometer with effective wavelength of 0.65 μm for Al_2O_3 in the process of heating for the first (a) and second (b) sphere passages over the specimen. In the second oscillogram one can clearly see the peak produced by the flash. Figure 3 shows results of measurements of the directional spectral radiation coefficients for Al_2O_3 in the brightness temperature range 2080-2375 K.

The uncertainty in the measurements of the hemispherically directional spectral reflection coefficient does not exceed 2%, while the uncertainty in measurements of the thermodynamic temperature of the irradiated surface over the range 2000-2500 K comprised 0.5%.

NOTATION

$E^0_{\lambda T}$, spectral radiation density of black body at temperature T; $E^0_{\lambda Tb}$, spectral radiation density of black body at temperature T_b; C_1, constant in Planck radiation law, $C_1 = 3.7413 \cdot 10^{-16}$ W/m²; C_2, constant in Planck radiation law, $c_2 = 1.4388 \cdot 10^4$ μ·deg; λ, wavelength, μm; T, temperature, deg; T_b, brightness temperature, deg; θ, polar angle; φ, azimuthal angle; dω, elementary solid angle; $\varepsilon_\lambda(\theta, \varphi, T)$ directional spectral emissivity; $\alpha_\lambda(\theta, \varphi, T)$ directional spectral absorption capability; $\rho_\lambda(2\pi, \theta, \varphi, T)$ directional hemispherical spectral reflection coefficient: $\rho_{B\lambda}(2\pi, \theta, \varphi)$, hemispherical directional spectral reflection coefficient of MS-20 milk glass; $L(2\pi, \theta, \varphi)$, specimen brightness in direction defined by angles θ from entire hemisphere; L_0; sphere wall brightness.

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RADIATIVE PROPERTIES OF COMPOSITE MATERIALS BASED ON PHENOLIC CARBON AND GLASS REINFORCED PLASTICS

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The article investigates the change of radiative characteristics of composites based on carbon, quartz, and glass fabric and phenol formaldehyde resin in dependence on the wavelength, the temperature, and thermal effects.

Information on the radiative properties of composite materials (CM) is indispensable for the solution of problems of heat exchange, and also for the calculation and design of structures subjected to intense thermal loading. Investigation of the behavior of the radiative characteristics of CM in dependence on the temperature and other factors is also required when new compositions are devised, for their comparative evaluation and the selection of the most promising ones.

Materials based on composites of heat-resistant fabrics and phenol formaldehyde resin are in practice one of the most important groups of heat-protective coatings. They can be used for the protection of surfaces in a broad range of thermal fluxes including very large

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