

To determine the spectral absorptance of a material the authors use a method that modulates the monochromatic radiation incident on the specimen and directly compares the absorbed power with electrical power released in the specimen.

The radiative properties of a material, i.e., emission, absorption, reflection, and transmission of radiation, are important thermophysical characteristics used in calculations of heat transfer, in optical pyrometry and in light technology [1-3]. However, at present reliable data are missing for many technically important materials. The number of such materials is increasing, and the required intervals of operating temperature and wavelength are expanding.

The absorptance and emittance are the same only under conditions of thermodynamic equilibrium [1-2]. Therefore to measure the absorptance is an important problem in its own right. It can be determined even at low temperatures, when the thermal emission is still low. A radiative flux is incident on the specimen surface, and the absorptance is calculated from the temperature increase. Here we can measure the absorptance in terms of the ratio to the total or the partial emission of thermal sources with a specific temperature, and of any other radiative sources. For example, data on absorption of solar radiation are an important application.

The calorimetric method of determining absorptance is used in two variants: steady-state and dynamic. In the steady-state variant the absorbed radiative power is determined from the specimen temperature [4, 5], and in the dynamic variant it is determined from the rate of specimen temperature increase [6]. In the first case one must know the coefficient of heat transfer from the specimen (the temperature derivative of the heat transfer), and in the second case one must know the specimen specific heat.

This method of measuring the spectral absorptance is as follows. The surface of the specimen investigated is irradiated periodically with pulses of monochromatic radiation. As a result of the radiative absorption the average temperature increases, and there are oscillations of specimen temperature about the mean value (during the light pulses the temperature increases, and it falls in the intervening intervals). The increase of average temperature depends on the mean radiative absorptance and the heat transfer coefficient, and the amplitude of the temperature oscillations with short period is proportional to the absorbed power, and inversely proportional to the specimen heat capacity.

Heating by modulated incident light is widely used at present to determine the specific heat, and is one variant of the modulation calorimeter (see the reviews in [7, 8]). Because of the periodic nature of the temperature variations they are recorded by the use of selective amplification and synchronous detection. This ensures high sensitivity and allows the measurement to be made with temperature oscillations on the order of 0.01°K. In specific heat measurements the power of the light radiation absorbed by the specimen was not determined, and therefore the measurements were relative.

To use this method to determine spectral absorptance we must know the power and frequency of the incident radiation pulses, the amplitude of the temperature oscillations arising, and the specimen specific heat. However, we can use the compensation measurement method, in which we need not know the specimen specific heat, and the temperature oscillations are measured by reducing them to zero [9]. To do this the specimen receives pulses of electric current, additional to the incident radiation pulses (Fig. 1). If we make the electric pulse power equal to the absorbed radiation power, the total power released in the specimen remains constant, and the temperature oscillations stop. The incident radiative power can be determined with

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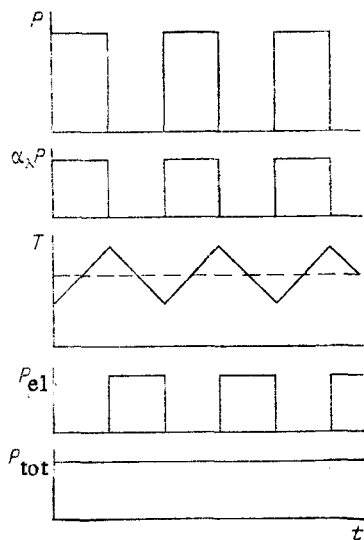


Fig. 1. Timewise diagrams illustrating the method of measuring the spectral absorptance.

the aid of instruments which use a perfect blackbody [10, 11], or with the aid of an auxiliary specimen coated with a layer of known absorptance. When the compensation measurement method is used sensor temperature calibration is not required. The electric power released in the specimen can be measured to an accuracy of about 1%.

The advantages of this method of measurement are self-evident: high sensitivity, making it possible to measure very small temperature oscillations; wide range of operating temperatures; increased measurement accuracy by using the compensation method. There are limitations deriving from the nature of the method: for the measurements one needs thin specimens possessing sufficient electrical conduction.

This method of measurement was checked on a special experimental equipment (Fig. 2). The radiative source was a halogen incandescent lamp of nominal power 500 W. The filament current was controlled by an autotransformer and was measured by the ammeter of the electrodynamic system. We used a high-transmission type MDR-2 monochromator. The input and output slits were removed, and their positions were occupied, respectively, by the lamp and the specimen for the measurements. We used a diffraction grating with 300 lines/mm (the wavelength interval is 0.8–2.5  $\mu\text{m}$ , the back dispersion is 8 nm/mm). After the monochromator the radiative flux passes through a type IKS-1 infrared light filter.

An electromagnetic relay was used to modulate the radiation incident on the specimen. To its moving part was attached a rod with a metal flag which completely intercepted the radiative flux when the relay operated. The contacts of the same relay were used to switch on and off the current in the specimen. The modulation period was set by a rectangular pulse generator.

The specimens for the measurements had thickness 0.05–0.1 mm, length 40 mm and width 2 mm. The central part of length 20 mm was singled out by means of welded or soldered potential leads. The junction of a copper–constantan thermocouple was attached to the back surface of the specimen. A thin layer of rubber cement served to insulate the thermocouple from the specimen electrically.

To measure the thermal emf we used the photocompensation amplifier. The amplifier output voltage was supplied to the input of a plotter operating in the time sweep mode. The electrical current pulses were generated with the aid of a stabilized source. The current in the circuit and the voltage drop over the central part of the specimen were measured with digital voltmeters. To eliminate parasitic emf's the direction of the circuit current could be changed with the aid of a switch.

The specimens were located in a vacuum chamber. For measurement at room temperature it was enough to pump down with a fore-vacuum pump, achieving a vacuum on the order of 0.1 N/m<sup>2</sup>. The modulation period was 10 sec. This was required to create temperature oscillations of sufficient amplitude in the specimen, several hundredths of 1°K.

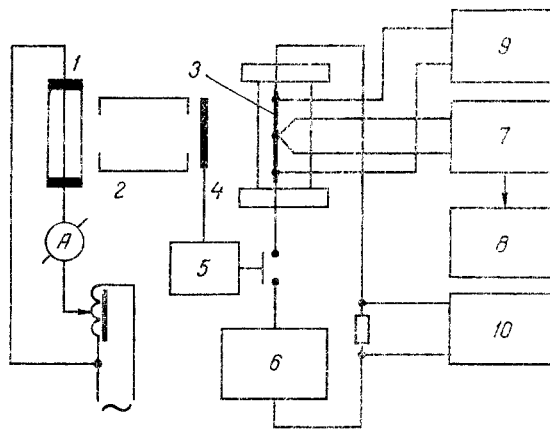


Fig. 2. Schematic diagram of the equipment to measure the spectral absorptance: 1) light source; 2) monochromator; 3) specimen; 4) modulator; 5) relay; 6) dc electrical source; 7) photo-compensation amplifier; 8) plotter; 9, 10) digital voltmeters.

To measure spectral absorptance we used two methods, the compensation method and the comparison method. In the compensation method we gradually increase the power of the electrical pulses in the specimen, supplementing the monochromatic radiation pulses; here each time we measure the amplitude and phase of the temperature oscillations. The amplitude of the temperature oscillations was linear vs the power of the electrical pulses, and when the electrical power became larger than the absorbed radiative power, the phase of the temperature oscillations changed by  $180^\circ$ . In drawing the graph of these oscillations we drew the amplitude negative (Fig. 3). The points of intersection of the lines obtained with the horizontal axis correspond to the radiative power absorbed by the specimen.

The power of the incident radiation was determined with the aid of a specimen coated with a layer of carbon black, for which the spectral absorption was assumed to be 1. In particular, the technique was: after the measurements of absorbed radiative power the surface of the specimen was coated with a layer of black, and then the measurements were repeated. This method has the advantage that one need not take into account possible differences in width of the specimens.

In the comparison method, after recording the temperature oscillations in the specimen the radiative source was switched off, and electrical pulses were generated in the specimen of the same duration and of amplitude such that roughly the same temperature oscillations were obtained. By comparing the amplitudes of the temperature oscillations for these measurements, from the electrical power one can easily calculate the power of monochromatic radiation absorbed by the specimen. The incident radiative power was also determined with the aid of a blackened specimen.

In using the compensation method one cannot completely stop the temperature oscillations in the specimen. The reason is that the light pulses have a trapezoidal shape, while the electrical pulses are rectangular. Therefore, when the electrical pulses are switched on and off the total power differs from the average. However, the time of rise and fall of the light pulses is 0.2-0.3 sec, and the illumination time is 5 sec. Because of this favorable ratio this difficulty is not important and does not prevent a correct determination of the spectral absorptivity. A technique for reducing this effect is known [9]: the current pulses are generated not with a relay, but with an amplifier which is controlled by a photosensor perceiving the light incident on the specimen. Then the electrical pulses also become trapezoidal, and the variation of total power at the times of switching can be considerably reduced.

The measurements on specimens of thickness 0.05 and 0.1 mm showed that for an absorbed radiative power of 1 mW or more the scatter of the measured results does not exceed 5% (Fig. 4). A complete analysis of the errors in determining the spectral absorptivity is as yet difficult, but one can expect that the total error of the measurements will not exceed 10%.

In order to increase the sensitivity and expand the wavelength interval it is useful to replace the monochromator by a set of interference light filters [12]. This increases the useful flux of monochromatic radiation, especially in the longwave part of the spectrum, while

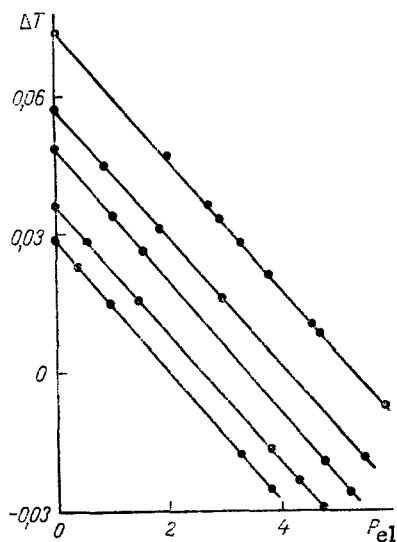


Fig. 3

Fig. 3. Amplitude of temperature oscillations in the specimen as a function of the electrical pulse power. The lines correspond to different thicknesses of a layer of black paint on the specimen surface: for the lowest line  $\alpha_\lambda = 0.39$ , and for the top line 1. The quantity  $\Delta T$  is in  $^{\circ}\text{K}$ , and  $P_{e1}$  is in mW.

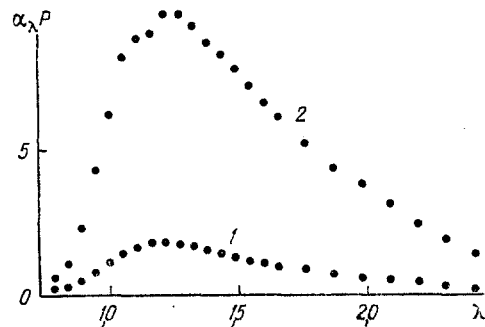


Fig. 4

Fig. 4. Measured dependence of the power absorbed by the specimen as a function of wavelength: 1) original specimen; 2) blackened. The spectral absorptivity was practically constant and equal to  $0.18 \pm 0.01$ . The quantity  $\alpha_\lambda P$  is in mW, and  $\lambda$  is in  $\mu\text{m}$ .

retaining quite high resolution. By using radiative sources of high power and more favorable spectral content one can measure specimens with considerably less absorptivity, and can also enlarge the wavelength interval.

To check the applicability of the method at elevated temperatures we recorded temperature oscillations in the specimen from oscillations of its electrical resistance. The specimens were heated to the required temperature by direct current, and the required electrical power pulses were generated by alternating current.

A comparison with the methods presently used to measure the spectral absorptivity of materials confirms that the proposed method has specific advantages in many cases. The practical implementation of the method is quite simple, and the preparation of specimens for the measurements has no special difficulties. One can use specimens in the form of strips of conducting materials (metals, alloys, semiconductors) of thickness on the order of 0.1 mm, conducting or dielectric coatings on such strips having thickness on the order of 0.01 mm, conducting coatings of thickness up to 0.1 mm on dielectric substrates of any thickness.

#### NOTATION

$P$ , power of the monochromatic radiation incident on the specimen;  $\alpha_\lambda$ , spectral absorptivity of the specimen;  $\alpha_\lambda P$ , radiative power absorbed by the specimen;  $P_{e1}$ , electrical power of the pulses in the specimen;  $P_{\text{tot}}$ , total power released in the specimen;  $T$ , specimen temperature;  $\Delta T$ , amplitude of the temperature oscillations;  $\lambda$ , wavelength.

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## RADIATIVE PROPERTIES OF THERMALLY PROTECTIVE MATERIALS

### BASED ON PHENOLIC ASBESTOS-PLASTICS

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A study was made of the radiative characteristics of composites based on asbestos-capron and asbestos-polyformaldehyde as a function of wavelength, temperature, and heating regimes.

It is necessary to study the radiative properties of thermally protective materials (TPM) and their dependence on wavelength, temperature, and heating parameters in order to develop formulas for thermally protective coatings for use under given conditions.

One of the most promising groups of TPM's contains materials based on composites of asbestos-bearing fillers and phenolformaldehyde resin. The available literature data on the radiative characteristics of phenolic plastics is very limited and applies mainly to coke residues of phenolic carbon and phenolic nylon at  $T > 2500^\circ\text{K}$  [1]. At the same time, study of the radiative properties of phenolic asbestos-plastics in the temperature range 1100-2000°K is of considerable interest. Here, it should be noted that the radiative properties of the composite in this temperature range are determined not only by the characteristics of the coke residue of the binder, but also to a significant extent by the filler. Depending on the temperature and the heating parameters in the surface layer, it is possible to have different relationships between the filler and coke residue and, thus, a significant difference in the optical properties of composites.

Here we report results of measurements of the normal hemispherical reflectivity  $\rho_{\lambda_n, 2\pi}$  of a TPM at the wavelength 0.58  $\mu\text{m}$  and of spectral normal emissivity  $\epsilon_{\lambda_n}$  in the range 1-9.5  $\mu\text{m}$ . The TPM was a composite based on asbestos-capron, asbestos-polyformaldehyde, and phenolformaldehyde resin. The TPM was tested in the working-temperature range. The relative error of  $\epsilon_{\lambda_n}$  in the range 1-9.5  $\mu\text{m}$  and of  $\epsilon_{\lambda_n} = 1 - \rho_{\lambda_n, 2\pi}$  at 0.58  $\mu\text{m}$  was no greater than 4%, with a confidence level no lower than 0.95. The measurements were made with a negative pressure of 13-1.3 Pa ( $10^{-1}$ - $10^{-2}$  mm Hg).

Normal hemispherical reflectivity was determined by comparing reflected radiation from the specimen and a standard — magnesium oxide — by means of the relation

$$\rho_{\lambda_n, 2\pi} = \left( \frac{J_{\lambda_n}^s}{J_{\lambda_n}^{st}} - \frac{J_{\lambda_n}^{sp}}{J_{\lambda_n}^{st}} \right) \rho_{\lambda_n, 2\pi}^{st}, \quad (1)$$

where  $J_{\lambda_n}^s$ ,  $J_{\lambda_n}^{sp}$ , and  $J_{\lambda_n}^{st}$  are the spectral luminance of the total (characteristics and reflected) radiation, the characteristic radiation of the specimen, and the luminance of the standard;  $\rho_{\lambda_n, 2\pi}^{st}$  is the normal hemispherical reflectivity of the standard. The specimen and standard were placed at the center of an integrating sphere. The radiation sources used were high-pressure quartz mercury lamps with a linear spectrum. The sources were located in the rear of the sphere relative to the direction of sighting of the half behind the specimen. Repeated

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