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INVESTIGATION OF THE EMISSIVE CHARACTERISTICS OF TRANSLUCENT FABRICS AND FILMS

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The method, experimental setup, and results of investigation of the integral emissivity, transmissivity, and reflectivity of translucent fabrics and films have been presented.

Fabrics and flexible translucent (semitransparent) films are widely used in thermal-protection and thermal-regulation systems in various fields of technology, in particular, as multilayer and flexible heat insulation [1–4]. Information on the emissive characteristics of the optimum thermal-protection structures in which the above elements are used is necessary for adequate computational analysis, designing, and creation of such structures. The special properties of measurements of the emissive characteristics of translucent materials, including fabrics and films, are determined by the difficulties associated with separation of the intrinsic and foreign radiant fluxes through the specimen under study and with determination of the specimen's temperature. The existing methods of measurement of the integral normal emissivity of translucent materials that are presented in the literature, in particular, in [5–9], are based on elimination of foreign radiant fluxes. Implementation of these methods requires that the experimental equipment be much more sophisticated than the analogs for investigation of opaque specimens. The specimen under study and the heater are in the chamber, whereas the radiation detector is outside the chamber. However the above methods and equipment ensure a low accuracy of measurement, which is still further reduced in investigations of fabrics and films because of the additional difficulties associated with determination of their temperature.

Below we present a method that is based on measurements and comparison of the effective emissivity of the specimens under study with two different opaque substrates of known differing emissive characteristics. Determination of the effective emissivity is carried out at the same temperatures by measuring the radiant fluxes of a rotating specimen with a substrate in the isothermal zone of heating with a controlled temperature. The method presented differs from the existing ones and enables one to determine both the normal and hemispherical emissivity, transmissivity, and reflectivity of the specimens under study in a wide temperature range. This is of particular importance for fabrics since their emissive characteristics are inconsistent with the Lambert law because of their specific physical structure, which makes it impossible to determine the hemispherical emissive characteristics on the basis of the known normal characteristics. Thus, the possibilities of investigating translucent materials, including fabrics and films, are extended.

The method of determination of the integral emissivity is based on the rotation of the specimen under study in the isothermal zone of heating with a controlled temperature and measurements of the specimen's radiant flux by a radiation detector introduced into the heating zone.

Figure 1 gives a diagram of the experimental setup for determination of the integral hemispherical and normal emissivity, transmissivity, and reflectivity of translucent fabrics and films. The setup consists of vacuum chamber 1 on which a mechanism of rotation of a specimen is placed; the mechanism consists of an electric motor with a regulated rotational velocity and shaft 2 hermetically introduced into the chamber. The experimental specimen 3 of a round shape with a diameter d is fastened to an opaque substrate — a heat-insulated metallic disk 4 having the same diameter as the specimen. A coating with known emissivity and reflectivity is applied to the surface facing the specimen. The substrate is secured on a plane holder which is rigidly joined to the shaft. A layer of heat-insulating material ensuring heat insulation of the metallic substrate is placed between the holder and the substrate. The total thickness of the specimen, the substrate, and the heat-insulating material can attain 50 mm. The sample is heated with a plane radiation ohmic heater 5.

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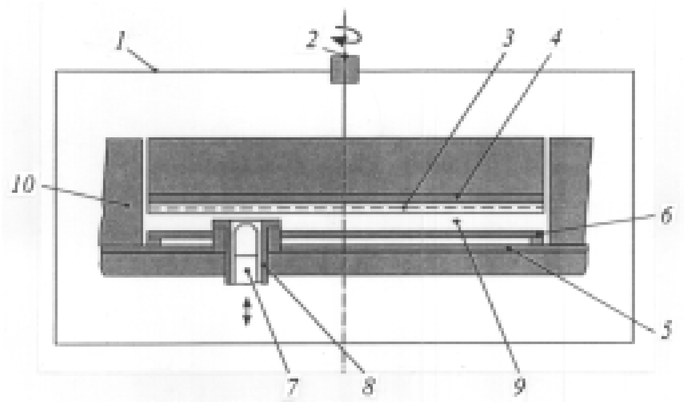

Fig. 1. Diagram of the experimental setup for measurements of the integral emissive characteristics of translucent specimens.

Between the heater and the specimen, there is a plane disk 6. The heater and the disk have coaxial holes at a distance *r* from the center of rotation of the specimen for the radiation detector 7; the radiation detector is placed inside a cooled copper tube 8, whereas its detecting surface is in the upper end plane of the tube. In such a manner, we ensure the possibility of measuring practically the hemispherical radiant flux and the emissive characteristics of the specimen. In the cases where it is necessary to measure the normal emissive characteristics of the specimen we move the detector to a corresponding depth inside the tube. Thermocouples 9 are installed on the circle with a radius *r* in the gap between the disk 6 and the specimen to determine the specimen's temperature. To ensure isothermality in the zone of heating of the specimen a part of the heater, which is beyond the specimen, is also faced with heat insulation 10.

Before the measurements, we calibrate the radiation detector, the thermocouples, and the device for determination of the pressure in the chamber. Calibration of the radiation detector is carried out with the isothermal spherical model of a black body directly under operating conditions in the vacuum chamber (at a residual pressure of the gas in the chamber of less than 1 Pa). To calibrate the thermocouples by the comparison method we use a reference platinum-rhodium thermocouple. The device for measuring pressure is also calibrated by the comparison method with the use of reference devices. Furthermore, the emissive characteristics of the substrates 4 are checked, when the occasion requires, directly under operating conditions and in the corresponding temperature ranges before and after testing the specimens under study.

The temperature dependences of the integral hemispherical emissive characteristics of a specimen are determined in the course of two runs of tests with different metallic substrates in which the surfaces facing the specimen have differing values of emissivity and reflectivity. The test are carried out as follows. We produce a vacuum in the chamber and apply regulated electric power to the heater. Once the thermal regime of the heaters, the disk, and the rotating specimen has been stabilized, we measure the radiant flux and the specimen's temperature and the pressure of the gas in the chamber. Within the framework of the two runs of experiments, the radiant fluxes are measured at the same temperatures. According to the results of the tests, we can write the following relations:

$$E_1 = \varepsilon_s \sigma T_s^4 + \varepsilon_{d1} \sigma T_{d1}^4 \tau_s (1 + \rho_s \rho_{d1} + \rho_s^2 \rho_{d1}^2 + ...) + \varepsilon_s \tau_s \rho_{d1} \sigma T_s^4 (1 + \rho_s \rho_{d1} + \rho_s^2 \rho_{d1}^2 + ...) \,, \tag{1}$$

$$E_2 = \varepsilon_s \sigma T_s^4 + \varepsilon_{d2} \sigma T_{d2}^4 \tau_s (1 + \rho_s \rho_{d2} + \rho_s^2 \rho_{d2}^2 + ...) + \varepsilon_s \tau_s \rho_{d2} \sigma T_s^4 (1 + \rho_s \rho_{d2} + \rho_s^2 \rho_{d2}^2 + ...) \,. \tag{2}$$

The expressions in the parentheses on the right-hand sides of (1) and (2) allow for the effects of rereflection between the specimen and the substrate and represent infinitely decreasing geometric progressions. In the case where the specimen is in close contact with the substrate (adhesion), allowance is made only for the first term of the progression. Owing to the heat insulation on the back side of the substrate and the lateral heat insulation, we can assume that $T_s = T_d$. After the substitution of the sums of progressions and simple transformations, Eqs. (1) and (2) are reduced to the form

$$E_1 = \left(\varepsilon_s + \frac{\varepsilon_{d1}\tau_s}{\varepsilon_s + \tau_s + \rho_s\varepsilon_{d1}} + \frac{\varepsilon_s\tau_s\,\rho_{d1}}{\varepsilon_s + \tau_s + \rho_s\varepsilon_{d1}} \right) \sigma T_s^4 \, , \tag{1$'$}$$

$$E_2 = \left(\varepsilon_s + \frac{\varepsilon_{d2}\tau_s}{\varepsilon_s + \tau_s + \rho_s\varepsilon_{d2}} + \frac{\varepsilon_s\tau_s\,\rho_{d2}}{\varepsilon_s + \tau_s + \rho_s\varepsilon_{d2}} \right) \sigma T_s^4 \, . \tag{2$'$}$$

Furthermore, by definition with allowance for the Kirchhoff law and the law of conservation of energy, for the specimen and the substrates we can write the relations

$$\varepsilon_s + \tau_s + \rho_s = 1 \, , \tag{3}$$

$$\varepsilon_{d1} + \rho_{d1} = 1 \, , \quad \varepsilon_{d2} + \rho_{d2} = 1 \, . \tag{4}$$

By simultaneous solution of Eqs. (1′), (2′), (3), and (4) we obtain

$$\begin{aligned} \varepsilon_s = {} & \frac{1}{\rho_{d1}\,(\varepsilon_{d2} - \varepsilon_{\text{eff2}}\,\rho_{d2}) - \rho_{d2}\,(\varepsilon_{d1} - \varepsilon_{\text{eff1}}\,\rho_{d1})} \Big\{ (\varepsilon_{\text{eff2}}\,\rho_{d1}\varepsilon_{d2} - \varepsilon_{\text{eff1}}\,\rho_{d2}\varepsilon_{d1}) - \\ & - \Big\{ (\varepsilon_{\text{eff2}}\,\rho_{d1}\varepsilon_{d2} - \varepsilon_{\text{eff1}}\,\rho_{d2}\varepsilon_{d1})^2 + [\rho_{d1}\,(\varepsilon_{d2} - \varepsilon_{\text{eff2}}\,\rho_{d2}) - \rho_{d2}\,(\varepsilon_{d1} - \varepsilon_{\text{eff1}}\,\rho_{d1})] \times \\ & \times [\varepsilon_{d1}\varepsilon_{d2}\,(\varepsilon_{\text{eff1}} - \varepsilon_{\text{eff2}}) - \varepsilon_{\text{eff1}}\varepsilon_{\text{eff2}}\,(\varepsilon_{d2}\,\rho_{d1} - \varepsilon_{d1}\,\rho_{d2})] \Big\}^{1/2} \Big\} \, , \end{aligned} \tag{5}$$

$$\tau_s = \frac{\varepsilon_{\text{eff1}}\varepsilon_{d1} - \varepsilon_s\,(\varepsilon_{d1} - \varepsilon_{\text{eff1}}\,\rho_{d1}) - \varepsilon_s^2\,\rho_{d1}}{2\varepsilon_s\,\rho_{d1} + (\varepsilon_{d1} - \varepsilon_{\text{eff1}}\,\rho_{d1})} \, , \tag{6}$$

where

$$\varepsilon_{\text{eff1}} = E_1/(\sigma T_s^4) \, ; \quad \varepsilon_{\text{eff2}} = E_2/(\sigma T_s^4) \, .$$

The analysis of (5) and (6) yields that it is expedient to use (on the substrates) coatings differing in ε_d and ρ_d as much as possible to ensure the highest accuracy. In particular, if a "black" coating satisfying the black-body model, in which $\varepsilon_d = 1$ and $\rho_d = 0$, is used on one substrate, relations (5) and (6) are simplified and acquire the form

$$\varepsilon_s = \varepsilon_{\text{eff1}} - \left[\varepsilon_{\text{eff1}}^2 - \varepsilon_{\text{eff1}}\varepsilon_{\text{eff2}} - \frac{\varepsilon_{d2}}{\rho_{d2}}\,(\varepsilon_{\text{eff1}} - \varepsilon_{\text{eff2}}) \right]^{1/2} \, , \tag{5$'$}$$

$$\tau_s = \varepsilon_{\text{eff1}} - \varepsilon_{\text{eff2}} \, . \tag{6$'$}$$

Next, with account for the emissivity ε_s and transmissivity τ_s obtained, we determine from (3) the reflectivity

$$\rho_s = 1 - \tau_s - \varepsilon_s \, . \tag{7}$$

The experimental setup enables us to carry out investigations of the radiation characteristics in the range of temperatures T = (300–900) K under vacuum conditions. The copper tube and the interior chamber walls are cooled by liquid nitrogen. Apart from fabrics and films, we can investigate specimens from solid-state translucent materials of thickness to 2 mm. The diameter of the specimens, the substrates, and the heat insulation adjacent to them are equal to 150 mm. The heat-insulation thickness is equal to 48 mm. The metallic substrates are manufactured from a 2-mm-

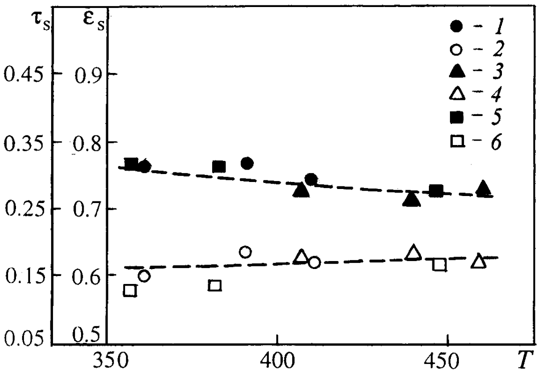

Fig. 2. Integral emissivity (1, 3, and 5) and transmissivity (2, 4, and 6) of glass cloths: 1 and 2) yellow cloth, 3 and 4) green cloth; 5 and 6) black cloth. *T*, K.

thick copper plate. The radiation detector and the thermocouples are at a distance of 50 mm from the center of the specimen.

The front (facing the specimen) surface of the first substrate satisfying the black-body model can be manufactured relatively simply in the form of a rough ribbed surface formed by triangular grooves and steps. To this surface, we apply a "black" coating whose emissivity is more than 0.92. Then, if the angle of divergence of the sides of the grooves is less than 60°, the effective emissivity of the surface is more than 0.99 [10].

On the smooth front surface of the second substrate, it is expedient to use silver or gold coatings whose emissive characteristics are $\varepsilon_{d2} < 0.05$ and $\rho_{d2} > 0.95$.

The structural parameters of the experimental setup have been optimized so as to ensure the isothermality of the specimens under study and minimization of systematic errors caused by the reduction in the temperature of the portions of the specimen's surface in traversal above the cooled radiation detector and copper tube and by the effects of reflection of the radiant fluxes from the specimen's surface to negligible values. The analysis of the accuracy of measurement has shown that the errors of determination of the emissive characteristics on the setup are no higher than 7%.

The method and setup developed have successfully been used for investigation of different fabrics, in particular, glass cloths employed as external shields in shield-vacuum heat insulation. Three cloths having the same structure but differing in color (yellow, green, and black) were investigated in the temperature range 360–460 K. The results of the tests are presented in Fig. 2 in the form of the temperature dependences of the integral hemispherical emissivity and transmissivity.

In consideration of the data obtained, we can note the following aspects:

(a) the temperature dependences of the emissivity coincide for all the specimens studied; the values of the emissivity decrease only slightly from 0.77 at T = 360 K to 0.72 at T = 460 K;

(b) the temperature dependences of the transmissivity also coincide for all the specimens; the values of the transmissivity are constant, in practice, and are equal to 0.17 in the temperature range indicated above;

(c) the values of the reflectivity of the specimens, obtained from relation (7) with allowance for the data of Fig. 2, increase only slightly from 0.09 (T = 360 K) to 0.11 (T = 460 K).

Thus, the integral emissive characteristics of the cloths studied in the temperature range 360–460 K are independent of color.

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NOTATION

E, radiation density recorded by the radiation detector in the tests; ε_s, τ_s, and ρ_s, emissivity, transmissivity, and reflectivity of the specimen; ε_{d1} and ε_{d2}, ρ_{d1} and ρ_{d2}, emissivity and reflectivity of the first and second substrates;

$\tau = 5.67 \cdot 10^{-8}$ W/($\mathrm{m}^2 \cdot \mathrm{K}^4$), Stefan–Boltzmann constant; *T*, absolute temperature. Subscripts: 1 and 2, first and second runs of tests; s, specimen under study; d, substrate; d1 and d2, first and second substrates; eff, effective.

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