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REFLECTANCE OF HEAT SHIELD MATERIALS UNDER

RADIANT—CONVECTIVE HEATING

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A procedure is presented for determining the spectral emissivity and surface temperature of heat shield materials subjected to radiant—convective heating by using the radiant component of the heat flux.

In order to determine the temperature of a surface and to calculate the heat balance, it is necessary to know the emittance of the material under investigation. It depends on many parameters, such as the properties of the material itself, the structure of the surface, the temperature, and the wavelength and direction of propagation of the radiation. Performing calculations which take account of the direction and wavelength dependence of the radiative characteristics of a material is a rather tedious process even when very large computers are used [1]. However, the reflection indicatrices of many heat shield materials correspond to diffuse radiation within an angle of $\sim 50°$ from the normal to the working surface [2]. It was shown in [3] that the directional dependence of the optical properties of a surface must be taken into account only for specularly or nearly specularly reflecting surfaces, and that a simple model of diffuse reflection gives values which are in good agreement with a more detailed analysis and with existing experimental data.

It follows from the energy balance for an irradiated surface of an opaque material and Kirchhoff's law that

$$\rho(\lambda) = 1 - \varepsilon(\lambda),$$

from which the emittance of a surface can be found by using the reflection method [1, 4].

The measurement of the temperature of a surface subjected to radiant—convective heating requires taking account of or completely eliminating high fluxes of reflected radiation. This is commonly done by using choppers to separate the self- and reflected radiation from a surface [5]. The total intensity of the radiation from the sample surface is measured, and then while the incident radiation is cut off by the chopper, the intensity of the self-radiation from the material is measured. By measuring the intensity of the radiation reflected from the surface of a standard, the intensity of the radiation incident from the radiant heating source is determined. From these data and the formula for the heat balance, the reflectance of the surface of the material is

$$\rho(\lambda) = \frac{\beta_\Sigma(\lambda) - \beta_{self}(\lambda)}{\beta_0(\lambda)}, \tag{1}$$

where $\beta_\Sigma(\lambda) = \beta_{self}(\lambda) + \beta_{refl}(\lambda)$.

The true temperature of the surface is determined with a formula which follows from Wien's law:
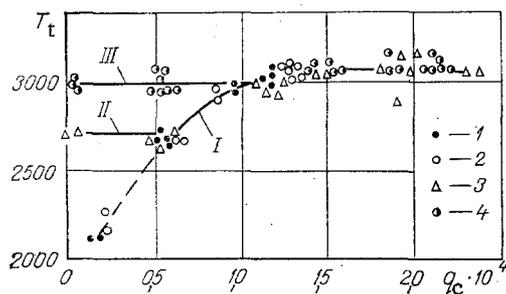
Fig. 1. Variation of surface temperature of asbestos textolite under 1) convective heating; 2) radiant heating; 3, 4) combined heating for q_r = 6300 and 10,500 kW/m^2; I, variation of T_t for convective, radiant, and combined heating when $q_c > q_r$; II, III, variation of T_t under combined heating when $q_c < q_r$. q_c in kW/m^2, T_t in °K.

$$T_t^{-1} = T^{-1}(\lambda) + \frac{\lambda}{C_2} \ln \varepsilon(\lambda). \tag{2}$$

At the present time this is practically the only method which permits the determination of the surface temperature of materials subjected to radiant or combined radiant—convective heating, if there are no dips in the radiation spectrum of the heating source. However, the use of choppers not only complicates the measurements, but also has a substantial effect on the degradation of the material [6]. Under combined heating with parabolic radiant energy concentrators [7] the use of choppers is very difficult.

We discuss a method of determining the reflectance and surface temperature of heat shield materials in which the heated sample surface is irradiated with an additional source of radiation. For this purpose, there are generally used modulated sources with a strength which is negligibly small in comparison with that of the heating device, so as not to change the heat balance at the surface of the material under study. However, in combined radiant—convective heating of a sample it is practically impossible to separate even a modulated signal from the intense reflected radiation. In view of this, it was decided to use the radiant component of the heating as the source of additional radiation, having first estimated its contribution to the heat balance, the surface temperature, and the rate of degradation of the material. To this end, a series of experiments was performed on a radiant-plasma heating arrangement [7] under combined radiant—convective heating for various ratios of the radiant and convective components of the heat flux, and also for separate radiant and convective heating.

Samples of asbestos textolite whose emissivity at a surface temperature of 3000°K was taken equal to 0.8 were studied. The spectral intensity of the radiation from the surface was measured with an FÉP-4 photoelectric pyrometer at a wavelength λ = 0.65 μm. Figure 1 shows the dependence of T_t obtained for constant values of the radiant flux of 6300 kW/m^2 (points 3) and 10,500 kW/m^2 (points 4) while the convective component of the heating was varied from zero to 23,000 kW/m^2. The figure also shows the dependence of T_t of the material separately for convective (points 1) and radiant (points 2) heating.

It is clear that under combined heating, when the convective heat flux is larger than the radiant flux, T_t agrees with the surface temperature obtained under convective heating only (curve I). Thus, it follows that if the surface temperature obtained under convective heating is higher than its equilibrium value under radiant heating, then under combined heating for the same values of the radiant and convective heat fluxes it will be equal to T_t for convective heating. The same rule holds also when the radiant component of the heat flux predominates (curves II and III). Similar results were obtained in studies of samples of carbonaceous plastic and fiberglass reinforced plastic.

Let us consider under what conditions T_t and $\varepsilon(\lambda)$ will be the same under the various heating regimes we are considering. If the surface of the material is raised to a given temperature by convective or radiant heating, then for many materials, particularly for fiberglass reinforced plastics, the structure of the surface will be appreciably changed, and consequently it will have a different reflectance. In our case of convective and combined

TABLE 1. Calculated and Experimental Degradation Character-
istics of Quartz Glazed Ceramics

Material	$q_0 \cdot 10^{-4}$	$q_r \cdot 10^{-4}$	$J_e \cdot 10^{-4}$,	Γ	$\varepsilon(\lambda)$	T_t, K	G_Σ	G_Σ^{calc}
	kw/m²		kJ/kg				kg/m² · sec	
Quartz glazed ceramic (100% SiO₂)	1,06	1,0	1,25	0,67	0,64	2830	0,91	1,03
	1,06	—	1,25	0,88	0,64	2830	0,51	0,47
Quartz glazed ceramic (SiO₂+0,5% Cr₂O₃)	1,035	1,0	1,25	0,59	0,83	2900	1,22	1,18
	1,035	—	1,25	0,9	0,83	2900	0,42	0,39

radiant—convective heating, a stream of gas blowing on the surface with the same intensity
left the external form of the sample surfaces under study practically unchanged. However,
from the heat balance equation for the surface of a material being degraded

$$\frac{q_0 + \varepsilon(q_r - \sigma T_t^4)}{G_\Sigma} = \bar{c}(T_t - T_0) + \Gamma[\Delta Q_w + \gamma(J_e - J_w)] \tag{3}$$

it is clear that with an increase of the heat flux supplied by the radiant component, the
surface temperature can remain unchanged only if the rate of degradation of the material in-
creases proportionally.

To test this requirement we performed experiments on samples of quartz glazed ceramics,
whose surfaces are relatively unaffected by heat fluxes, and for which it is possible to take
$\Delta Q_w \approx 11,000$ kJ/kg [8]. In addition, the experimental conditions enabled us to estimate the
gasification coefficient under convective and combined heating. The velocity of the incoming
gas stream was chosen in such a way that the spreading film of melt was not entrained by the
stream, but solidified on the lateral surface of the water-cooled support. This made it pos-
sible to weigh it after the end of the experiment and to determine the entrainment of the ma-
terial in the liquid phase.

In order to be able to calculate $\varepsilon(\lambda)$ with Eq. (1), the experiment was performed in the
following sequence. The material sample was first tested under combined heating which satis-
fied the condition that the radiant component of the heat flux was smaller than the convec-
tive component. After $\beta_\Sigma(\lambda)$ was measured, the radiant heater was disconnected and $\beta_{self}(\lambda)$
was determined under convective heating. The intensity of the radiation from the radiant
heating source $\beta_0(\lambda)$ was first found under these same conditions by measuring the radiation
reflected from a standard covering of magnesium oxide on a water-cooled calorimeter.

By using the results obtained, the total ablation of material during convective and com-
bined heating was calculated by using formulas which follow from the heat balance Eq. (3).
In calculating the amount of heat radiated by the surface it was assumed that the spectral
and total emittances were the same. The calculated and experimental results are listed in
Table 1. Experiment and calculation show that increasing the heat flux by increasing the
radiant component leads to a proportional increase in the ablation rate of the material.
The values of the degradation parameters of quartz glazed ceramics were obtained from 10-12
samples for each kind of test. The data were processed statistically.

The error in the determination of G_Σ was 12%, $\varepsilon(\lambda)$ 12%, and T_t 6%. In the calculation
of the systematic error of the measurements of $\varepsilon(\lambda)$ and T_t, Eqs. (1) and (2) were differen-
tiated. Since the intensity of the radiation was measured by using the FÉP-4 pyrometer tem-
perature scale, its relative error was calculated with the formula

$$\frac{\delta\beta(\lambda)}{\beta(\lambda)} = \frac{C_2 \exp[C_2/\lambda T(\lambda)]}{\lambda T^2(\lambda)\{\exp[C_2/\lambda T(\lambda)] - 1\}} \delta T(\lambda),$$

where $\delta T(\lambda)$ is the systematic error due to the accuracy of the pyrometer. The random error
was determined with a confidence coefficient of 0.95.

It should be noted that the satisfactory agreement of the calculated and experimental
values of the degradation rate of a material shows that the values of $\varepsilon(\lambda)$ and T_t were deter-
mined accurately enough by the proposed method. The experimental results listed in Table 2
are a good proof of the satisfactory accuracy of the method.

TABLE 2. Measured Values of $\varepsilon(\lambda)$ and T_t of Samples of Quartz Glazed Ceramics (100% SiO_2)

Sample No.	$q_c \cdot 10^{-4}$, kW/m²	$q_r \cdot 10^{-4}$, kW/m²	$\beta_0(\lambda) \cdot 10^{-12}$, W/m³	$\varepsilon(\lambda)$, $\lambda=0,65$ μm	T_t^c, °K	T_t^Σ, °K
1	1,43	1,0	3,02	0,64	2800	2800
2	1,43	1,0	3,02	0,65	2835	2860
3	1,43	1,0	3,02	0,65	2835	2800
4	1,43	1,0	3,02	0,65	2835	2860
5	0,92	0,5	1,62	0,64	2765	2750
6	0,92	0,5	1,62	0,65	2750	2710
7	1,43	0,5	1,62	0,62	.2850	2900
8	1,43	0,5	1,62	0,62	2850	2900
9	0,42	0,5	1,62	0,64	2620	2620
10	0,42	0,5	1,62	0,64	2600	2620

Table 2 lists the calorimetric heat fluxes and, therefore, for samples No. 9 and 10 the relation $q_0 > q_R$ is satisfied all the same, since the radiant flux received by the surface because of reflection will be smaller than the convective. The emissivity should not vary significantly over a relatively narrow range of temperatures (2600–2800°K). Calculation of its values with Eq. (1) gave practically identical results (Table 2), in spite of the fact that the quantities entering the formula, including the radiation incident on the sample from the radiant heating source, are appreciably different. The difference of the values of the surface temperature of the samples under convective and combined heating lies within the limits of error of the experiment. It should be noted that since the film of melt of the quartz glazed ceramic is semitransparent to the radiant heat flux, in our case we can speak only of a certain effective emissivity which is typical of the whole thickness of the molten film.

As an example, Fig. 2 shows the variation in the intensity of the surface radiation according to the FÉP-4 pyrometer temperature scale in the process of quasistationary degradation of samples of asbestos textolite and quartz glazed ceramics. At the very start of the experiment when the material has not been heated up and there is no film of melt on the surface, the reflectance of the samples of quartz glazed ceramics (100% SiO_2) is appreciably
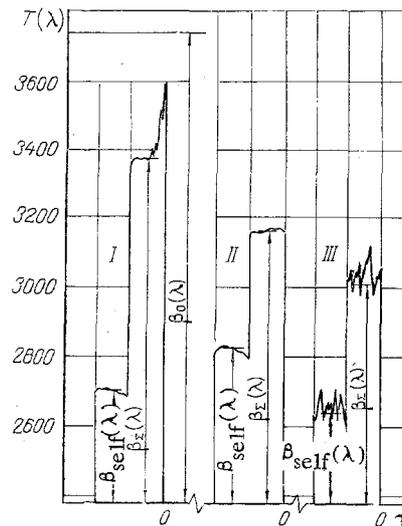
Fig. 2. Tracings of radiation intensity variation from the surface of samples of some heat shield materials (according to the pyrometer temperature scale) in the process of their degradation under combined $\beta_\Sigma(\lambda)$ and convective $\beta_{self}(\lambda)$ heating: I, quartz glazed ceramic (100% SiO_2); II, quartz glazed ceramic (SiO_2 + 0.5% Cr_2O_3); III, asbestos textolite. The τ axis is directed from right to left. $T(\lambda)$ in K; τ in sec.

TABLE 3. Values of T_t and $\varepsilon(\lambda)$ for $\lambda = 0.65$ μm of Some Heat Shield Materials for $q_c = 12,600$ kW/m² and $q_r = 5000$ kW/m² ($\beta_0(\lambda) = 1.56 \cdot 10^{12}$ W/m³)

Material	$\beta_\Sigma(\lambda) \cdot 10^{-12}$, W/m²	$\beta_{self}(\lambda) \cdot 10^{-12}$, W/m³	$\varepsilon(\lambda)$	T_t, °K
Fiberglass reinforced plastic with phenol binder	0,327	0,132	0,88	2500
Carbonaceous plastic	1,84	1,59	0,86	3500
Bakelite	1,44	1,30	0,9	3350
Quartz glazed ceramic ($SiO_2 + 0.5\%\ Cr_2O_3$)	0,551	0,282	0,83	2750
Asbestos textolite	0,673	0,38	0,8	2860
Teflon	0,04	$8,25 \cdot 10^{-8}$	0,33	1000
Fiberglass reinforced plastic with silicone binder	0,435	0,187	0,84	2610

higher than its value for quasistationary degradation (diagram I). Temperature fluctuations (diagram III) arise from the separation of solid particles from the surface of the asbestos textolite.

Table 3 lists the values of $\varepsilon(\lambda)$ and T_t for $\lambda = 0.65$ μm of some heat shield materials. A coke layer is formed on the surface of all the materials except quartz glazed ceramic and Teflon in the heating process. This is responsible for the high values of the emissivity. The data obtained for heat shield materials with phenol and epoxy binders are in satisfactory agreement with the results in [2].

The surface temperature of heat shield materials during high-temperature heating is one of the most important characteristics. The improvement of methods and the accuracy of its measurement is an extremely time consuming problem, particularly under intense radiant–convective heating. The method we have proposed for measuring $\varepsilon(\lambda)$ and T_t is distinguished by simplicity, but unfortunately cannot claim high accuracy. Moreover, the effect of gaseous ablation products of the material contained in the boundary layer may lead to an increase of the error of the measurements. However, since at the present time there are no more accurate methods available for determining $\varepsilon(\lambda)$ and T_t under radiant–convective heating, this method can be recommended for the quasistationary degradation of materials.

NOTATION

$\rho(\lambda)$, $\varepsilon(\lambda)$, spectral reflectance and emittance; $\beta_\Sigma(\lambda)$, $\beta_{self}(\lambda)$, $\beta_{refl}(\lambda)$, spectral intensity of total, self, and reflected surface radiation; $\beta_0(\lambda)$, spectral intensity of incident radiation from heating source; λ, wavelength at which measurements are performed; C_2, pyrometric constant; $T(\lambda)$, T_t, brightness temperature and true temperature of surface; T_0, initial temperature of material sample; q_0, convective heat flux supplied to undegraded surface; q_c, q_r, calorimetric convective and radiant heat fluxes; q_R, radiant heat flux received by surface; ε, total emittance of surface; J_e, J_w, enthalpy of gas at outer edge of boundary layer and at the surface temperature of the material; $\bar{c}$, average specific heat of material in the temperature range from T_0 to T_t; Γ, gasification coefficient of material; G_Σ, G_Σ^{calc}, experimental and calculated ablation rates; ΔQ_w, thermal effect of physicochemical transformations; γ, injection coefficient for laminar boundary layer equal to 0.6; σ, Stefan–Boltzmann constant; $\delta\beta(\lambda)$, $\delta T(\lambda)$, systematic errors of measurement of radiation intensity and temperature; T_t^c, T_t^Σ, true temperatures of surface under convective and combined radiant–convective heating.

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MODEL FOR THE CALCULATION OF THE COMPLEX HEAT TRANSFER
IN HIGH-TEMPERATURE IR EMITTERS

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A mathematical model of the complex heat transfer in high-temperature IR emitters is proposed, together with a procedure for its numerical realization.

Recently, the technique of infrared heating has been steadily more widely used in technological processes of the radioelectronics industry, precision engineering, and other branches of the national economy. In particular, the modules for IR heating first proposed by the present authors and produced on the basis of series halogen quartz lamps have proved effective for high-temperature processes [1].

However, in designing the corresponding equipment, considerable difficulties arise because of the inadequacies of existing methods of calculating the radiational and complex heat transfer, both in the IR module itself and in the working volume of the thermoradiational devices. The main problem of module design here is the determination of the temperature of its quartz shell, which must be in the range 700-1250°K. A lower temperature leads to disruption of the halogen cycle, and hence to a sharp reduction in the life of the lamp, while a higher temperature reduces the mechanical strength of the quartz shell, which may lead to its rapid breakdown. In addition, calculation of the heat transfer in the working volume requires a knowledge of the spectral composition of the IR-module radiation, which depends not only on the supplied potential but also on the structure of the module.

The most general version of the module structure will be considered (Fig. 1a). It consists of a tungsten spiral 1, enclosed in a gas-filled quartz shell 2, which, within the limits of the angle β, is coated externally with a highly reflective metallic layer. Between the frame 3 and the reflective coating, there circulates a cooling fluid. Energy transfer within the shell 2 occurs both by radiation and by convection.

The free surface of the shell is surrounded externally by air, and may be subjected to the influence of external radiation. In view of the symmetry of the problem, only the half-length of the cylindrical-shell cross section will be considered. Taking the relatively small thickness of shell 2 in comparison with its radius into account, its temperature field is calculated in a plane approximation (Fig. 1b). For the formulation of the mathematical model, the following additional conditions are assumed: 1) the temperature and heat-transfer coefficients from the shell to the gas on both sides are known and constant; 2) the quartz shell absorbs and emits energy, but does not scatter it; 3) the spiral and the shell are non-gray bodies, whose specific heat, thermal conductivity, and radiational properties do not depend on the temperature; 4) the radiation intensity of the spiral considerably exceeds the intensity of intrinsic emission of the shell and, in considering the energy transfer across the shell, the latter may be neglected.