STUDY OF RADIATIVE HEAT TRANSFER IN VACUUM-POWDER INSULATION BY INFRARED SPECTROSCOPY

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The optical spectral characteristics of materials used in vacuum-powder heat insulation are measured. A method is also developed for calculating the radiant conductivities of these materials, and some examples are presented.

Highly dispersed materials are widely employed in cryogenic technology for the creation of low-temperature thermal insulation. Heat transfer is mainly effected by conduction and radiation in evacuated insulating materials. These mechanisms interact with one another and, strictly speaking, should never be considered separately. However, in certain particular cases the representation of the total heat transfer as the sum of the two independent components is an entirely acceptable approximation. Depending on the type of insulation, either one or the other form of heat transfer may predominate. In vacuum-powder insulation based on aerogel and pearlite about 90% of the heat is transferred by radiation.

Studying the contribution of radiation to the total heat transfer of insulating materials, Van der Held [1] derived an equation for the apparent radiant thermal conductivity a long way from the boundaries of the medium,

$$\lambda_r = \frac{16n^2\sigma_0 T^3}{3\gamma}. \tag{1}$$

The attenuation coefficient for the radiation of a dispersed medium may be determined optically from the measured transmission and reflection coefficients. In various experimental investigations regarding radiant heat transfer in insulating materials based on the method of infrared spectroscopy [2-4], either no allowance has been made at all for the scattered radiation (with consequent serious errors) or, alternatively, only the integrated optical characteristics of the light-scattering media have been determined. Such data are, accordingly, only suitable for the particular temperatures and sources of radiation used in their original derivation (i.e., for temperatures of the order of 800-1800°K). In the present investigation we measured the hemispherical transmission coefficients D_λ for a layer 1 mm thick and the reflection coefficients $R_{\lambda\infty}$ of an optically "infinitely thick" layer in the spectral range 0.4-25 μ for several powder materials [5] used in making vacuum-powder thermal insulation in cryogenic technology (Fig. 1a, b).

For this purpose we used SF-4 ($0.4 \le \lambda \le 1.5\ \mu$) and IKS-12 ($1.0 \le \lambda \le 25\ \mu$) spectrometers with adapters enabling both the reflected radiation and the radiation transmitted by the sample to be focussed on the receiver [6, 8]. The values of D and R_∞ obtained in the SF-4 instrument to an accuracy of 0.5-1.5 and 1-2%, respectively, were used to introduce corrections into the results of the measurements carried out by means of the IKS-12 instrument, which contained a hemisphere as collecting element. These corrections were determined by comparing the D and R_∞ values obtained in the SF-4 and IKS-12 instruments in the spectral range 1-1.5 μ.

The accuracy of the D and R_∞ measurements in the medium and far infrared parts of the spectrum is 3% for λ = 1.5-5 μ and 10% for λ = 10-25 μ. For mixtures of aerogel with 20 and 40% bronze powder (BPI) the errors in measuring D over the spectral range 15-25 μ increase to 20-30%.

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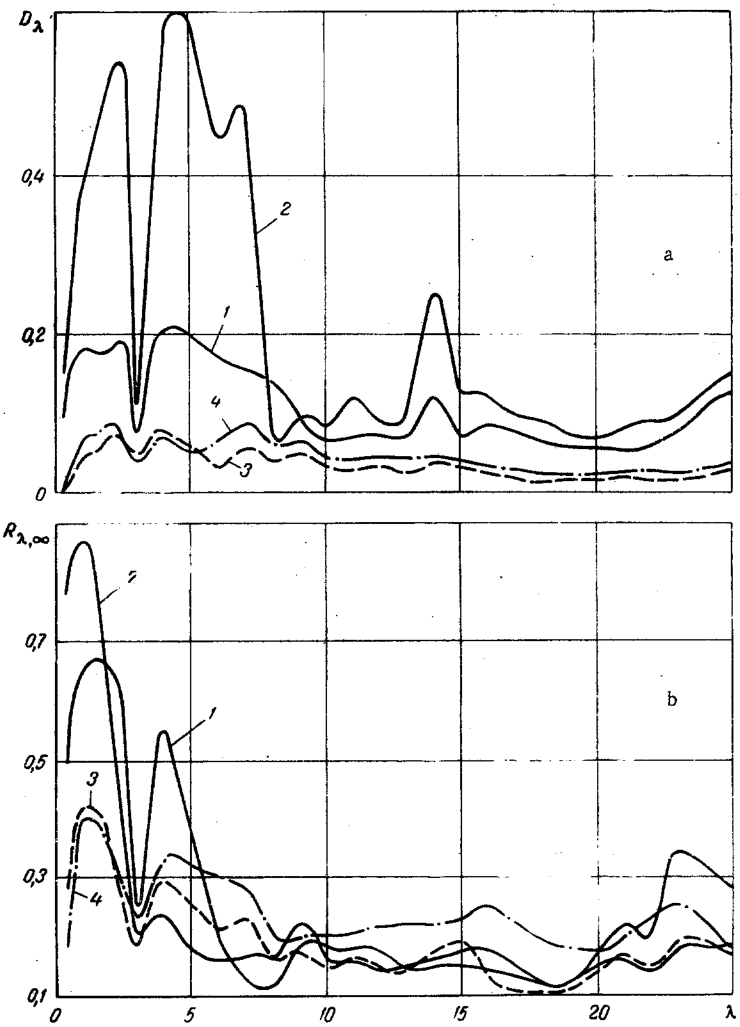

Fig. 1. Transmission coefficient of insulating powders (l = 1 mm) (a) and reflection coefficient of optically infinitely thick layers of the same insulating powders (b) as functions of infrared wavelength λ (in μ): 1) pearlite powder (bulk density ρ = 100 kg/m^3); 2) aerogel (ρ = 100 kg/m^3; 3) mixture of 80 wt. % aerogel and 20 wt. % BPI bronze powder (ρ = 130 kg/m^3); 4) mixture of 60 wt. % aerogel and 40 wt. % BPI bronze powder (l = 0.5 mm, ρ = 170 kg/m^3).

In order to calculate thermal conductivities from optical properties it is essential to know the integrated radiation attenuation coefficients. We developed a method of determining these coefficients from the results of spectrophotometric experiments for any radiation-source temperatures, including cryogenic. We shall here introduce the concept of the effective temperature of radiant transfer T_r. The apparent radiant conductivity λ_r of the insulation between bounding surfaces held at temperatures T_1 and T_2 is

$$\lambda_r \sim (T_1 + T_2)(T_1^2 + T_2^2).$$

If the same insulating material is placed between surfaces at temperatures T_r and $T_r + dT_r$, we have

$$\lambda_r' \sim [T_r + (T_r + dT_r)]\, [T_r^2 + (T_r + dT_r)^2].$$

If we assume that $\lambda_r = \lambda_r'$, equate the right-hand sides of these equations, and neglect terms containing dT_r, we obtain

$$4T_r^3 = (T_1 + T_2)(T_1^2 + T_2^2).$$

TABLE 1. Integrated Optical Parameters of Insulation Materials and Radiant Conductivities of Vacuum-Powder Insulation for Boundary Temperatures of 90 and 300°K

Insulation material	α, 1/m	σ, 1/m	ν, 1/m	μW/cm·°K optical method	μW/cm·°K calorimetric method [5]
Pearlite powder	$1,2 \cdot 10^3$	$2,0 \cdot 10^3$	$3,2 \cdot 10^3$	9,1	9—10
Aerogel	$1,2 \cdot 10^3$	$1,8 \cdot 10^3$	$3,0 \cdot 10^3$	9,7	10—13
Mixture of 80 wt. % aerogel and 20 wt. % BPI bronze powder	$1,8 \cdot 10^3$	$2,7 \cdot 10^3$	$4,5 \cdot 10^3$	6,5	5—6
Mixture of 60 wt. % aerogel and 40 wt. % BPI bronze powder	$2,7 \cdot 10^3$	$6,7 \cdot 10^3$	$9,4 \cdot 10^3$	3,1	2—2,5

Hence,

$$T_r = \sqrt[3]{\frac{(T_1 + T_2)(T_1^2 + T_2^2)}{4}}\,. \qquad (2)$$

Figure 2 shows the hemispherical radiation (emission) spectrum of an absolute black body (curve 1) at a temperature T_r = 212°K (boundary temperatures 300 and 90°K), and also curves plotted for pearlite powder giving the spectral intensity distribution of the absolute black-body radiation reflected (curve 2) and transmitted (curve 3) by the sample at the temperature indicated; these curves represent the results of multiplying the ordinates of curve 1 (Fig. 2) by the reflection coefficients $R_{\lambda\infty}$ (Fig. 1b) and transmission coefficients D_λ (Fig 1a) of pearlite for each wavelength. The ratio of the areas under curves 2 and 3 to the area under curve 1 (Fig. 2), respectively, give the integrated hemispherical transmission and reflection coefficients of the sample D and R_∞. Knowing these quantities, we may find the single-scattering albedo ω and the optical thickness τ_0. The equations required for this purpose were given in [7]; for the conditions of the present investigation they may be simplified as follows:

$$D = (A_1 + 1)\exp(-\tau_0) - A_1 \exp(-k\tau_0) - \frac{a\,[A_2 \exp(-\tau_0) - A_1 a \exp(-k\tau_0)]\,[\exp(k\tau_0) - \exp(-k\tau_0)]}{\exp(k\tau_0) - a^2 \exp(-k\tau_0)} \qquad (3)$$

and

$$R_\infty = \frac{\omega}{4(1 - 1{,}6\omega)}\left[\frac{3(2k-3)}{3+2k} + 0{,}6\right], \qquad (4)$$

where

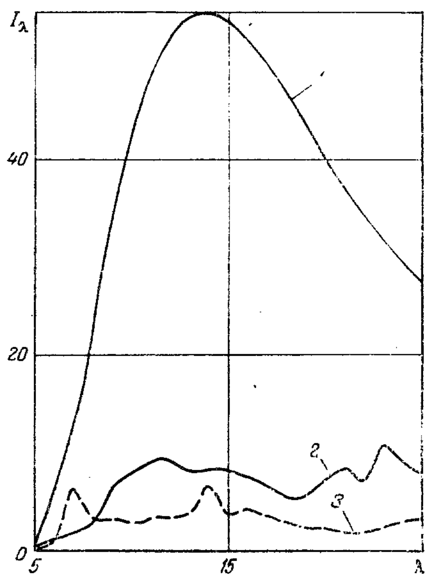

Fig. 2. Diagram to aid calculation of the integrated hemispherical optical parameters of perlite powder (I_r, W/m³; λ, μ): 1) Intensity of absolute black-body radiation at Tr = 212°K; 2) intensity of radiation reflected by an optically infinitely thick layer; 3) intensity of radiation transmitted by a layer 1 mm thick.

$$A_{1,2} = \frac{\omega}{4\left(1 \mp \frac{2}{3}\right)(1-1{,}6\omega)};$$

$$a = \frac{1-\frac{2}{3}k}{1+\frac{2}{3}k}; \quad k = \frac{3}{2}\sqrt{\frac{1-\omega}{1-0{,}25\omega}}.$$

For $\tau_0 = 1$ and $\omega = 0.1$–0.9 Eqs. (3) and (4) agree closely (2–3%) with the results of an exact numerical solution of the original integrodifferential equation carried out in an electronic computer.

For convenience of subsequent calculations Eqs. (3) and (4) were plotted graphically in coordinates of $D - \tau_0$ for $\omega = 0$–1 and $R_\infty - \log(1-\omega)$. The latter relationship enables us to determine ω directly from R_∞. Knowing ω and D and using the graphical representation of Eq. (3), we may find τ_0.

The integrated absorption, scattering, and total attenuation coefficients are related to ω and τ_0 as follows:

$$\alpha = (1-\omega)\tau_0/l; \tag{5}$$

$$\sigma = \omega\tau_0/l; \tag{6}$$

$$\gamma = \alpha + \sigma. \tag{7}$$

The values of these parameters for pearlite, aerogel, and mixtures of aerogel with 20 and 40 wt. % of BPI bronze powder, determined with errors of 12, 8, and 15%, respectively, are shown in Table 1. The addition of bronze powder to the aerogel has little effect on the absorption coefficient of the mixture because of the low absorbing power of metals in the longwave part of the spectrum. However, an increase in BPI content leads to a considerable rise in the scattering coefficient.

Introducing the effective radiant-transfer temperature and remembering that in vacuum-powder insulation the refractive index of the filling medium n = 1, Eq. (1) may finally be written in the form

$$\lambda_r = \frac{16\sigma_0 T_r^3}{3\gamma}. \tag{8}$$

Table 1 compares the radiant conductivities of vacuum-powder insulation obtained by the optical and calorimetric methods for boundary temperatures of 90 and 300°K. As indicated by these results, the optical method agrees with the calorimetric measurements (the accuracy of the latter being 5-7%). Spectroscopic measurements are simpler and less time-consuming, they determine the proportion of heat transferred by radiation directly, and may be successfully used for determining the radiant conductivities of effective thermal-insulation materials.

NOTATION

λ_r	is the apparent radiant conductivity;
D_λ, D	are the spectral and integrated hemispherical transmission coefficients;
$R_{\lambda\infty}$, R_∞	are the spectral and integrated hemispherical reflection coefficients of an optically infinitely thick layer;
α, σ, γ	are the integrated hemispherical absorption, scattering, and total attenuation coefficients;
τ_0	is the optical thickness;
ω	is the single-scattering albedo;
σ_0	is the Stefan—Boltzmann constant;
n	is the refractive index of the filling medium;
T_r	is the effective temperature of radiant transfer;
T_1, T_2	are the boundary temperatures;
l	is the thickness of dispersed layer;
λ	is the radiation wavelength;
I_λ	is the spectral intensity of the hemispherical radiation.

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