THE TEMPERATURE FUNCTION FOR THE INTEGRAL EMISSIVITY OF CERTAIN MATERIALS BELOW 300° K

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We present the method for and the results from an experimental investigation into the temperature function of the integral emissivity for certain materials used in low-temperature multilayer vacuum insulation. We study the effect of fiberglas filler materials on radiative heat transfer.

It is well-known that radiative heat transfer in low-temperature multilayer vacuum insulation makes up a substantial fraction of the total transferred heat [13, 16].

Emissivities for Several Materials at Temperatures of 77–90° K

Material	Here	Other authors
Aluminum foil	0.019	0.018 [1] 0.021
PETPh film (12.5 μm) from the aluminum-coated side	0.036	0.04*) [1]
the same, from the uncoated side	0.34	0.21 [11]

*The film has been coated with aluminum on both sides.

For a mathematical analysis of radiative heat transfer through insulation we must know the temperature function of the integral emissivity for the screens, and we must know the influence of the filler material on the radiative heat exchange between two radiation screens as a function of temperature.

When the insulation is used at boundary temperatures of 300–77° K, the wavelengths corresponding to maximum screen radiation are equal to 13.7–53.4 μm. The use of the function $\varepsilon(T)$ in accordance with the classical Drude formula

$$a = \varepsilon = 36.05\sqrt{\frac{\rho}{\lambda}} \tag{1}$$

for temperatures below 300° K because of the anomalous skin effect would result in a substantial error, although—as demonstrated by Hagen and Rubens—with this material at room temperature in the infrared region of the spectrum for wavelength >10 μm, this formula is in good agreement with the experimental data. Even if the calculation is carried out with consideration of the anomalous skin effect, such an error would not be excluded, since it is impossible to take into consideration the state of the screen surfaces. We were unable to use the values of the absorptivity (emissivity) available in the literature [1–3], since these correspond only to those conditions under which the radiation source exhibits a temperature close to 300° K, while the surface under consideration exhibits temperatures of 90, 77, 20.4, and 4.2° K.

For most metals and dielectrics subjected to radiation with $\lambda > 5$ μm, their absorptivity changes only slightly with a greater wavelength; to treat these as gray bodies in this case for this region of wavelengths is therefore quite valid. Proceeding from this fact, for temperatures <300° K the absorptivity and emissivity of the surfaces can be regarded as equivalent. On the basis of this assumption, the method proposed by the authors of [1–3] for the determination of ε reduces to the following. The outside surface of the inside container of Dewar-vessel-type calorimeter is fabricated of the material being investigated. The outside vessel with a known emissivity was kept at a temperature close to 300° K. Since the transfer of heat to the inside vessel is due entirely to radiation, the total heat flow, which is determined from the speed with which the cryogenic liquid boils away, can be expressed by the equation

$$Q = \frac{\varepsilon_1 \varepsilon_2 F_1 \sigma}{\varepsilon_2 + \varepsilon_1 (1 - \varepsilon_1) \frac{F_1}{F_2}} (T_2^4 - T_1^4), \tag{2}$$

from which we find ε_1.

With this method we cannot determine $\varepsilon(t)$, since we would have to know $\varepsilon_2(T)$ at temperatures <273° K; on the other hand, there exists a limited number of low-boiling liquids which would enable us to cover the temperature range 300–77° K.

We would also be unable to determine ε by the nonsteady low-temperature calorimetry method [4–6] based on the investigation of the change in the temperature of a heated specimen as it cools down. The assumption is made in this method that the emissivity and heat capacity of the material in the temperature range being studied is constant, and the essence of this assumption contradicts the purpose of measuring $\varepsilon(T)$.

The radiation method [7] is particularly cumbersome and calls for a surface standard with a known function $\varepsilon(T)$.

It is equally impossible to determine the integral $\varepsilon(T)$ for low temperatures with other methods [8, 9], so that we developed the following method.

In accordance with the Kirchhoff law, the emissivity of any body with respect to total and spectral radiation is always numerically equal to the absorption coefficient, given the identical values of λ and T, i. e.,

$$\begin{gathered} \varepsilon(T) = a(T), \\ \varepsilon(\lambda, T) = a(\lambda, T). \end{gathered} \tag{3}$$

The radiative heat exchange between two parallel surfaces of equal temperature is described by the

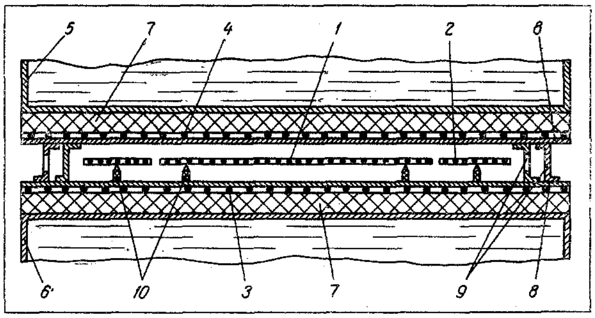

Fig. 1. Experiment for E(T) determination: 1–4) central, shielded, lower, and upper heaters; 5, 6) cryogenic vessels; 7) heat insulators; 8) temperature equalizers; 9) guard rings; 10) support elements.

Stefan-Boltzmann equation

$$q = \varepsilon_{\text{red}}\,\sigma (T_2^4 - T_1^4). \qquad (4)$$

If two surfaces of identical material are in a state of equilibrium and if their temperatures are sufficiently close, it can be assumed that $\varepsilon_1 \cong \varepsilon_2$, while on the basis of Eq. (3) their emissivity may be assumed to be equal to the absorptivity. In this case

$$\varepsilon_1 = \varepsilon_2 = \frac{2\varepsilon_{\text{red}}}{1+\varepsilon_{\text{red}}} \quad \text{or} \quad \varepsilon_{\text{red}} = \frac{\varepsilon}{2-\varepsilon}. \qquad (5)$$

The method for the determination of ε(T) thus reduces to maintaining two surfaces of identical material at various temperatures, with a temperature difference of 10–15° C, and determining the specific heat flow between these surfaces. The value of ε_{red} and ε are then found from Eqs. (4)–(5).

The experiments were carried out on a calorimeter [10] fitted out for the determination of the integral ε(T), as shown in Fig. 1. All of the measurements were carried out at a calorimeter pressure which did not exceed $7 \cdot 10^{-5}$ N/m^2. The top and bottom electrical heaters were attached through insulators to the bottoms of the cryogenic vessels; aluminum disks are mounted on the heaters to even out the temperatures. The center and the guard heaters are mounted on supports to ensure point contact. The center heater (120 mm in diameter) is mounted on three point supports with a high thermal resistance. The clearance between the center and guard heaters, on the one hand, and the clearance between the top and bottom heaters, on the other hand, amounted to 2.5–3.5 mm. Copper-constantan thermocouples were attached to the heaters, and then the materials to be tested. It should be noted that the test materials, after they were attached, exhibited a certain amount of roughness. The aluminum guard rings are designed to eliminate irradiation from the hot calorimeter parts. For this same reason, the orifices in the rings—designed to evacuate the space between the top and bottom heaters—are shifted relative to each other, and the inside surface of the outside ring has been blackened. To eliminate the parasite heat flow, the power-source wire and the thermocouples that lead to the center heater are attached at a distance of 150 mm to the guard heater, whose temperature was kept the same as that for the center heater throughout the experiment. Moreover, the presence of the guard heater seemingly enlarges the surface of the center heater, so that it may be assumed with sufficient accuracy that the emissivity being measured is "normal."

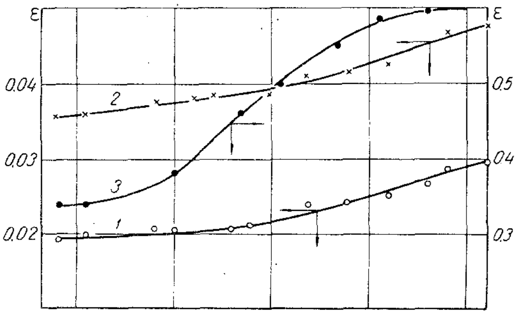

Fig. 2. Temperature dependence of integral emissivity of some surfaces: 1) aluminum foil; 2) aluminized side of 12.5 μ PETPh film; 3) the same, nonaluminized side.

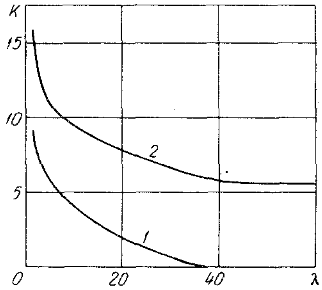

Fig. 3. Radiation transmission by some aluminized materials; 1) PETPh film; 2) SBR-M 40.

The heat flow is measured from the power supplied to the center heater. The temperature and current strength were measured by R-306 potentiometers operating in conjunction with M17/2 galvanometers, while the voltage is measured with a universal dc UPL-60-2 potentiometer. The total measurement error

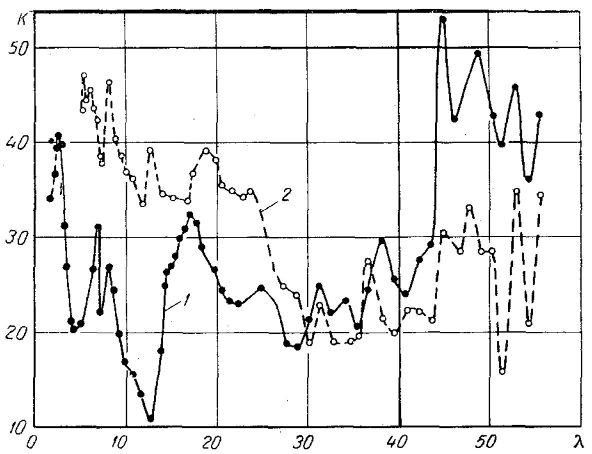

Fig. 4. Transmission spectra of fiberglas spacers: 1) SBR-M 40; 2) EVTI-10.

amounted to ±6%. The reproducibility of the results for either material fell within a range of ±2%.

The value of $\varepsilon(T)$ was determined for Al-brand aluminum foil (GOST 618-62) with a thickness of 14 μm, and for an aluminized polyethylene terephthalate film 12.5 μm in thickness, with the deposition thickness ranging from 0.025 to 0.03 μm (with coated and uncoated sides). We also determined the reduced emissivity for the cases in which the aluminum-foil surfaces being tested were separated by SBR-M40 glass-reinforced paper (a fiber diameter of 5–7 μm, a thickness of 40 μm, fabricated according to OAI.503.058 engineering specifications) and by EVTI-10 glass-reinforced fabric (fiber diameter 16–18 μm, thickness 100 μm, fabricated according to MRTU6 technical specification No. M-864-62).

The experimental results are shown in Fig. 2 . It should be noted that the values for the integral emissivity which we obtained for temperatures of 77–90° K are in good agreement with the measurements of other authors [1, 11], derived at an emitter temperature of 300° K (see table).

The materials were tested in the condition in which they were delivered from the factory, without any form of special machining or processing, with the exception of the degreasing of the aluminum foil.

As we can see from Fig. 2, the emissivity diminishes with a drop in temperature, i. e., with an increase in the radiation wavelength. The nature of the change in curves 1 and 2 within the temperature interval 300–90° K is smooth, which may suggest the absence within this range of explicit zones of absorption.

The great emissivity of the coated aluminium layer, in comparison with that of aluminum foil, cannot be explained exclusively by the thickness of the coated layer. The determination of the transmission of spectral radiation by this film in the range of wavelengths 2–56 μm, carried out with infrared IKS-14 and IKS-21 infrared spectrometers—modified for 56 μm with an echelette diffraction grating—demonstrated its complete opacity, just as the aluminum foil. The measurement accuracy for these devices was ±3%. It is interesting to note that with an aluminum coating thickness of 0.007–0.008 μm the film is already partially transparent for the indicated region of the spectrum (see curve 1, Fig. 3).

The propagation of the radiation in the metal is described by the equation

$$I = I_0 \exp\left(-4\pi\chi\frac{\delta}{\lambda}\right). \qquad (6)$$

In our case $-\chi = 5.47(\lambda/\rho)^{1/2}$, and Eq. (6) assumes the form

$$I = I_0 \exp\left(-21.88\pi\delta\sqrt{\frac{1}{\rho\lambda}}\right). \qquad (7)$$

Having carried out the calculations with consideration of formula (7) and the change in $\rho(T)$, we find the radiation attenuation I_0/I when $\lambda = 13.7$ and 50 μm for a film with a coating thickness of 3.03 μm in $e^{3.36}$ and $e^{6.35}$, respectively, while for a film with a coating thickness of 0.007 μm we find the attenuation in $e^{0.78}$ and $e^{1.49}$.

We can thus draw the following conclusions.

1. The reduction in the coating thickness below 0.025 μm is not advisable.

2. Exceeding the absolute values of the emissivity for the coated layer relative to that of the aluminum foil can be explained by qualitative changes in the crystal structure of the coated layer, and also by the possibility of the contribution made by the forces of surface tension to the intensity of the coated layer relative to the heat-treated foil. It should be expected that the emittance of the coated layer will approach that of the solid material as the thickness of the coated layer is increased.

Placing the fiberglas SBR-M40 and EVTI-10 fillers between the screens has virtually no effect on the magnitude of the radiative heat exchange between these, as we noted in [12]. This phenomenon can be explained by two factors: the emissivity of the fillers is no more than an order of magnitude larger than the emissivity of the screens, or their optical density is low. These conclusions follow from the analysis of the following equation of reduced emissivity for a system made up of two materials which are separated by screens:

$$\frac{1}{\varepsilon'_{red}} = \frac{1}{\varepsilon_{red}} + \frac{2}{\varepsilon_{sh}} - 1. \qquad (8)$$

Indeed, if $\varepsilon_{sh} > 10\varepsilon_1$, ε_2, (in our case $\varepsilon_{red} = 0.01$–0.019) we can write $1/\varepsilon'_{red} \cong 1/\varepsilon_{red}$, while if the optical density is small, the results of the study lead to Eq. (5).

We are not dealing with the mechanism of radiation transport in fiberglas materials in this article; this mechanism plays a substantial role, however, in general heat transport. The brief outline of the theoretical fundamentals of radiative heat exchange in such media was given in [13]. Reference [14] demonstrated that the radiant flux is attenuated primarily as a result of scattering in fiberglas vacuum insulation at temperatures of 367–700° K. In our case, where the dimensions of the glass fibers and the distances between these are commensurate with the radiation wavelengths, and the glass itself is not transparent, the attenuation of the radiant flux is extremely complex and in need of separate investigation.

Figure 4 shows the transmission spectra for SBR-M40 and EVTI-10 fiberglas fillers in the region of 2–56 μm, taken with the above-mentioned infrared spectrometers. It is easy to see that the transmission is extremely nonuniform and varies from 42 to 14% for various wavelengths. With an increase in the wavelength, the transmission initially diminishes, assuming its minimum value in the wavelength interval 8–45 μm, and then it again rises. The EVTI-10 filler is more transparent in the interval 2–28 μm and less transparent in the interval 37–56 μm.

Having analyzed the curves in Fig. 4 and having noted that from the experiments we have $1/\varepsilon'_{red} \cong \cong 1/\varepsilon_{red}$, we can assume, on the one hand, that the radiant flux—both direct and reflected, including the scattered reflection from the fibers—passes without hindrance through the openings in the filler lattice, and on the other hand, in view of the strong absorption by the glass fibers and their limited thickness, the absorbed energy is radiated to the receiver (the screen) without significant attenuation. Thus the assumption made here to the effect that the filler exhibits a high emissivity is quite valid.

The one-sided coating of the glass-reinforced paper with aluminum substantially reduce (to 5%) the transmission in the range 45–50 μm (curve 2, Fig. 3).

Examination of the glass-reinforced filler under a microscope showed that its structure is not uniform; we find both concentrations of fibers and areas in which they are much less dense; we note open slits (windows) 3–20 μm in size. Projections of the overall cross sections of the fibers through the slits onto a plane vary from 5 to 25 μm. The attenuation of the radiant flux in such a medium comes about as a result of its reflection, as well as because of the phenomenon of diffraction, since in first approximation the structure of the coating can be treated as a diffraction grating.

The problem of the diffraction of electromagnetic waves on flat metal gratings for a case similar to the one under consideration, i. e., when the period of the grating and the width of the slits are commensurate with the length of the incident wave, has been solved in [15].

Unfortunately, from our experiments it is impossible to determine the fraction of the attenuated radiant flux due to diffraction; however, we can state with sufficient justification that it is possible to employ coated latticed materials as insulation, particularly in low-temperature zones. The selection and fabrication of such materials must be based on the theoretical recommendations of [15] and the results presented in this paper.

NOTATION

ε is the integral emissivity; ε_{red} is the reduced emissivity; a is the absorptivity; ρ is the relative electric resistance ohm $\cdot$ mm^2/m; λ is the wavelength, μ; T is the temperature; σ is the radiation constant of an absolute black body; F is the surface area; q is the specific heat flux; χ is the absorption index; I_0 is the intensity of incident radiation; I is the radiation intensity with respect to the depth of δ-radiation; K is the coefficient of radiation transmission, %.

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