EFFECTS OF LOADING ON THERMAL AND ELECTRICAL
RESISTANCE OF CRYOGENIC INSULATION MATERIALS

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The dependence of electrophysical properties of thermal insulation materials on loading is studied. The data obtained are compared with the results of thermal resistance measurements.

One of the basic heat-transfer mechanisms in low-temperature thermal insulation is contact thermal conductivity, the role of which increases significantly with increase in external mechanical loading of the insulation. Due to the high complexity of dispersed systems, including thermal insulation materials, and additionally because of large departures from additiveness which occur in many cases under conditions of complex radiation – conduction heat transfer, estimation of the contribution of contact conductivity to total heat transfer is extremely difficult. Therefore, it is of great interest to develop methods for estimating this component which do not require performance of thermophysical experiments.

The present study will use a formal analogy between electrical and thermal resistance [1, 2] for the purpose of studying the dependence of contact thermal conductivity of insulating materials upon mechanical loading.

Measurements of the electrical resistance of specimens were performed with the apparatus shown in Fig. 1. The measurement chamber has a detachable hermetic case 5, in which the electrode system 1, 2, 3 is mounted upon insulators 9. The movable electrode 1, and thus the specimen 4, are loaded by the scales 6. Pressure on the specimen is transmitted through lever arm 10 and coupling rod 7. The coupling rod leaves the hermetic chamber through the thin rubber sleeve 8. The dial indicator 11 is used to measure specimen thickness. The weight of the movable part of the apparatus is compensated by balance weight 12. The conductors joining the electrodes to the measurement equipment are fed through a hermetically sealed connector in
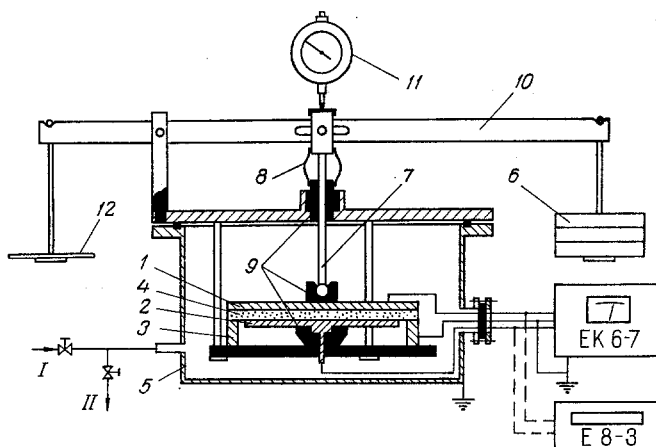

Fig. 1. Apparatus for determination of load dependence of electrical resistance and dielectric permittivity of insulating materials: 1, 2, 3) high-voltage, measurement, and guard electrodes; 4) specimen; 5) shell; 6) scales; 7) coupling rod; 8) hermetically sealed sleeve; 9) insulator; 10) lever arm; 11) dial indicator; 12) balance weight; I) dry nitrogen; II) to vacuum pump.

the shell. The latter is grounded and serves as a shield to avoid induction of stray signals into the electrodes.

To eliminate the effect of moisture upon the results, the specimen was heated to a temperature of 373-423°K, placed between the electrodes, and subjected to vacuum pumping for 3-4 h. After pumping was terminated the device was filled with dry nitrogen to atmospheric pressure and measurements were made over a loading range of 0-0.1 MPa.

The measurements were made with a three-electrode system with grounded guard electrode 3 to equalize the field between the high-voltage 1 and measurement 2 electrodes [3]. This method determines the volume resistance of the portion of the specimen included between electrodes 1 and 2. Measurements were performed with an EK6-7 teraohmmeter.

With this equipment the dependence of electrical resistance r_e upon mechanical loading P at 293°K was studied for three types of insulating materials: powdered (aerogel, perlite powder); sheet filament (SBR-M glass paper, ODP cellulose paper); and open-pore sheet polyurethane foam. These types are used in vacuum-powder and vacuum-multilayer cryogenic technology.

Similar functions of contact thermal resistance r_c over the temperature interval 293-90°K were studied for all materials. To do this special calorimetric measurements were performed with a plane calorimeter containing an attachment to compress the specimen [4]. The heat flux through the specimens at boundary temperatures of 293 and 90°K was determined from the quantity of oxygen evaporated from the main calorimeter chamber. The thermal resistivity was then determined from the expression

$$r_{ef} = \frac{\Delta T}{Q} F.$$

To find the contact component r_c of the total resistivity, the simplifying assumption of additiveness of radiation and conductivity was used. For parallel action of these mechanisms

$$r_c^{-1} = r_{ef}^{-1} - r_r^{-1}.$$

When the specimen is compressed the apparent radiant resistivity remains practically unchanged. Its value depends on the optical characteristics of the material — absorption and scattering coefficients, which for powdered and sheet filament insulation materials were determined by infrared spectroscopy [5, 6].

In the absence of data on the absorption and scattering coefficients of polyurethane foam, its attenuation coefficient was determined from calorimetric measurements. The asymmetric heating method of [7] with a plane calorimeter with heater on the hot wall was used to obtain the temperature dependence of the effective thermal conductivity coefficient of the polyurethane specimen, which was composed of 3-mm-thick sheets with a density of 70 kg/m³. The r_r value determined for polyurethane from this temperature dependence comprised 6.9 m²·deg K/W.

Original specimen thicknesses for P = 0 comprised 10 and 20 mm for the electrical and calorimetric measurements, respectively.

For aerogel and perlite (Fig. 2A) and polyurethane foam (Fig. 2B) the changes in r_e and r_c with loading are similar over practically the entire range studied. For filament materials (Fig. 2B) the dependence is similar in the load range 0.03 MPa for the glass paper and near 0.09 MPa for the cellulose paper, the predominant transfer mechanism here being thermal conductivity. The divergence in the values obtained for these materials at lower loading may be explained by inaccuracy in determination of r_c due to interaction of radiation and thermal conductivity, leading to disruption of the additive principle.

The electrical characteristic measurements show that aerogel and perlite have practically identical dependences of contact resistance on loading. For an increase in loading to 0.1 MPa the resistance falls by a factor of 30. The study of sheet materials shows that the polyurethane foam is more sensitive to loading, its contact resistance and load dependence being close to that of the powdered materials. The electrical resistance of the papers changes under compression to a significantly lower degree. The ODP paper resistance falls ≈ 7 times, while that of the SBR paper falls by less than a factor of 4. This agrees with the results of calorimetric studies [4], which demonstrated the high effectiveness of SBR glass paper as a gasket material in multilayer-vacuum insulation.

To verify the validity of the results obtained, measurements were also made of the dielectric permittivity ε of the insulating materials. An E8-3 digital capacitance meter was employed. Since that device
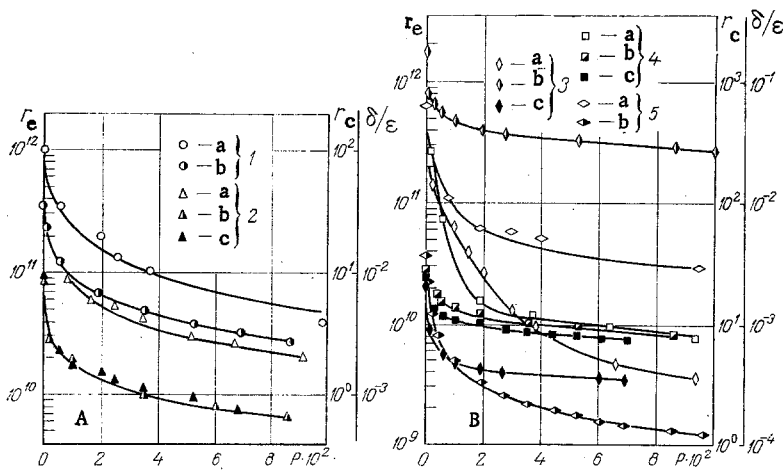
Fig. 2. Electrical characteristics (r_e, $\Omega \cdot m^2$; δ/ε, m) and contact thermal resistance (r_c, deg K $\cdot m^2$/W) for powdered (A) and sheet (B) thermal insulators vs mechanical loading (P, MPa): 1) aerogel; 2) perlite powder; 3) ODP; 4) SBR; 5) polyurethane foam; a) r_c; b) r_e; c) δ/ε.

operates at a frequency of 1 kHz, where the guard electrode does not function properly, a two-electrode system was used, with diameters of measurement and high-voltage electrodes equal to the specimen diameter. Because of the similarity of Poisson's equations for electrostatics [8] and thermal conductivity in the steady state [2], the dielectric permittivity is an analog of the thermal conductivity coefficient. Therefore, considering that r_c may be represented in the form $r_c = \delta/\lambda_c$, the electrostatic analog of r_c will be the quantity δ/ε.

As is evident from Fig. 2, the load dependences of the quantities r_e and δ/ε are similar.

Measurements of electrical resistance and capacitance as functions of mechanical loading were also made for a number of thermal insulation materials in [9]. Unfortunately, these data are not internally self-consistent nor consistent with results of contact thermal resistivity measurements.

Thus, analysis of the data obtained permits the conclusion that for thermal insulation materials the character of the change with mechanical loading of electrical resistance, the parameter δ/ε at 293°K, and contact thermal resistance in the temperature range 293-90°K is consistent for all materials studied. This makes it possible to use electrothermal analogy to study contact thermal resistivity in dispersed systems, eliminating the effect of the radiant component. Moreover, since in comparison to calorimetric techniques electrical measurements are more rapid and simpler, use of the methods considered here permits rapid qualitative assessment of the suitability of materials for use as cryogenic thermal insulation from the viewpoint of contact conductivity. This will permit reducing the number of calorimetric experiments needed in development of new effective compositions of these materials.

NOTATION

r_e, r_c, r_r, r_{ef}, electrical, contact, apparent radiant, and effective thermal resistivity; ε, dielectric permittivity; λ_c, coefficient of contact conductivity; Q, thermal flux through specimen; ΔT, temperature change across specimen; δ, specimen thickness; F, area of bottom surface of calorimeter chamber.

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A RHEOLOGICAL MODEL OF A THIXOTROPIC

VISCOELASTOPLASTIC MEDIUM

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A model is proposed which allows for the difference between instantaneous and slow deformations during loading and unloading (of a mixture based on mineral binding substances). At different constant deformation rates the model reflects the dependence of the relaxation phenomena on the velocity and describes the thixotropy loop.

In our investigations of the rheological properties of foam – concrete mixtures by the creep method under simple shear [1] and in the same medium (adobe) at a more mature age under axial compression and tension [2], as well as under simple shear in the presence or absence of normal stress [3-5], the difference between the instantaneous and slow deformations during loading and unloading was clearly and reliably traced. Therefore, we proposed a new rheological element, a ratchet with an imperfection, which can be called a generalized St. Venant element [1-5]. For the rheological description of media possessing fluidity this element is connected to the Schofield – Scott-Blair model as shown in Fig. 1; the series connection of the second Newton – St. Venant element to the indicated model provides the function $\dot{\gamma} = f(\tau)$ with a piecewise-linear character [1] by which we approximate the nonlinear fluidity curve.

When $\tau_c < \tau < \tau_d$ the equation of state of the model during loading, i.e., when the generalized St. Venant elements do not come into play, has the form

$$\tau - \tau_0 + \frac{\eta_1}{\eta_3}(\tau - \tau_c) + \left[n_1 + n_2\left(1 + \frac{\eta_1}{\eta_2} + \frac{\eta_1}{\eta_3}\right)\right]\dot{\tau} + n_1 n_2 \ddot{\tau} = \eta_1\dot{\gamma} + \eta_1 n_2\ddot{\gamma}. \tag{1}$$

When $\tau_0 < \tau < \tau_c$ the second term and $n_2\eta_1/\eta_3$ drops out of the left-hand side of Eq. (1).
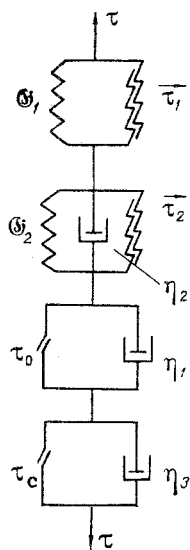

Fig. 1. Rheological model of a thixotropic medium with a nonlinear fluidity characteristic.