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# CONTACT CONDUCTIVITY OF CRYOGENIC HEAT INSULATION MATERIALS

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*Results are presented of an experimental investigation by the method of the electrothermal analogy for the contact heat transfer in different kinds of cryogenic thermal insulation and empirical dependences are obtained that permit execution of a qualitative, and in a number of cases, even a quantitative estimate of the contribution of the contact conductivity to the total heat transport through heat insulation.*

In principle, the possibility of an experimental study of contact heat conductivity in disperse materials by the method of the electrothermal analogy (ETA) was shown in [1]. This permits investigation of the contact heat conductivity in a pure form separate from its relationship to other heat transfer mechanisms by measuring the magnitudes of the material electrical resistivity under varying loads.

This paper is devoted to a more detailed study of the regularities of contact heat transfer in powder, fiber sheet, and multilayer systems utilized in cryogenic heat insulation.

We shall first examine the first two groups of materials. Analysis of the data obtained for them is facilitated by the possibility, verified in [2, 3], of utilizing the assumption of additivity of the radiation and conduction in such media.

Dependences of the specific electrical conductivity on the density are presented in Fig. 1 for a number of powder and sheet fibrous materials applied most extensively in vacuum-powder (VPI), vacuum-fiber (VFI), and vacuum-multilayer (VMI) heat insulations.

As is seen from the figure, the dependences mentioned are straight lines in logarithmic coordinates and are approximated by an expression of the form

$$\sigma \sim \rho^{k}. \tag{1}$$

The values of the exponent $k$ in this formula are given in Table 1 for the materials investigated.

Our data show that the specific electrical conductivity, and therefore, the contact thermal conductivity of pure powders (without metallic admixtures) and of packets of sheet fibrous materials vary in proportion to their density. The addition of metallic admixtures (particularly the bronze powder BPI) shielding the thermal radiation into powder insulation results in noticeable magnification of the dependence of the contact conductivity on the density. Because of the long duration of the experiment, there are practically no such data obtained by the calorimetric method. Only the dependence $\lambda_c$—$\rho$ for the mixture aerogel with 45 mass% BPI, shown in Fig. 1 for comparison and approximated by the expression

$$\lambda_c \sim \rho^{4,21}. \tag{2}$$

is presented in [4]. This dependence is in good agreement with an analogous expression for the mixture of aerogel with 40 mass% BPI but its somewhat greater steepness in the first case is due to the elevated content of metallic powder in the mixture.

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TABLE 1. Value of Exponents in Formulas (1), (5), and (6).

| No. | Insulation material | Exponent | | |
|---|---|---|---|---|
| | | $k$ (1) | $m$ (5) | $t$ (6) |
| 1 | Perlite | 1,04 | | |
| 2 | Aerogel | 0,94 | | |
| 3 | Aerogel + 20 mass% BPI | 1,36 | | |
| 4 | Aerogel + 40 mass% BPI | 3,14 | | |
| 5 | Glass fabric EVTI-7 | 1,20 | | |
| 6 | Paper from viscose and cellulose fibers | 0,93 | | |
| 7 | Basalt paper | 1,13 | | |
| 8 | Glass paper SBSh-S-T-5.5; | 1,07 | | |
| 9 | Glass paper SBR-M-40 | 0,96 | | |
| 10 | PET + EVTI-7 | | 0,052 | 0,35 |
| 11 | PET + paper from viscose and cellulose fibers | | 0,035 | 0,28 |
| 12 | PET + basalt paper | | 0,100 | 0,59 |
| 13 | PET + SBSh-C-T-5.5 | | 0,077 | 0,41 |
| 14 | PET + SBR-M-40 | | 0,110 | 0,92 |
| 15 | Al foil + SBR-M-40 | | 0,190 | 1,10 |

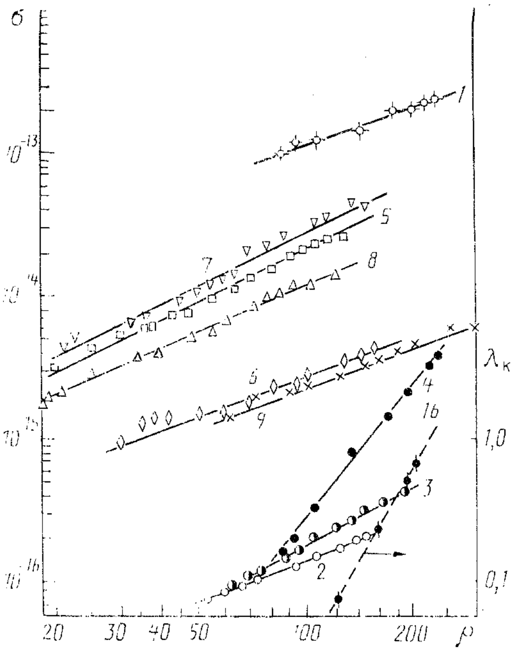

Fig. 1

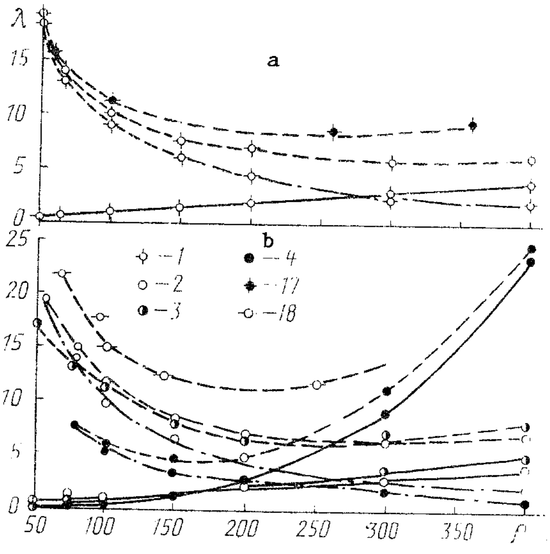

Fig. 2

Fig. 1. Dependence of the specific electrical conductivity σ, $\Omega^{-1}\cdot m^{-1}$ and the contact heat conductivity $\lambda_c$, mW/(m/K) of VPI and VFI on the bulk density ρ, kg/m$^3$; the numbers 1-9 correspond to Table 1, 16 is aerogel + 45 mass% BPI [4].

Fig. 2. Dependence of the heat conduction coefficient λ μW/(cm·K) of pearlite (a) and aerogel with its mixtures with bronze powder BPI (b) on the bulk density ρ, kg/m$^3$: the numbers 1-4 correspond to Table 1; 17 is pearlite [4]; 18 is aerogel [4]; solid lines are $\lambda_c$, dash-dot are $\lambda_p$, dashes are $\lambda_{ef}$.

Therefore, on the basis of the electrothermal analogy we can write for the contact thermal conductivity of VPI and VFI

$$\lambda_c = A\rho^k \tag{3}$$

TABLE 2. Computation of the Proportionality Factor in Formula (3) for VPI

| Insulation | $\rho$, kg/m$^3$ | Heat conductivity coefficient, μW/(cm·K) | | | A |
|---|---|---|---|---|---|
| | | $\lambda_{ef}$[4] | $\lambda_r$ [2] | $\lambda_c$ | |
| Aerogel | 100 | 10,9 | 9,7 | 1,2 | $1,6\cdot10^{-2}$ |
| Aerogel + 20 mass% BPI | 130 | 7,8 | 6,5 | 1,3 | $1,7\cdot10^{-3}$ |
| Aerogel + 40 mass% BPI | 170 | 4,7 | 3,1 | 1,6 | $1,6\cdot10^{-7}$ |
| Perlite | 100 | 10,1 | 9,1 | 1,0 | $8,3\cdot10^{-3}$ |

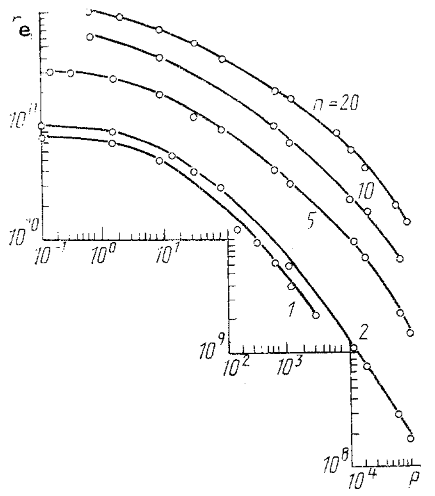

Fig. 3

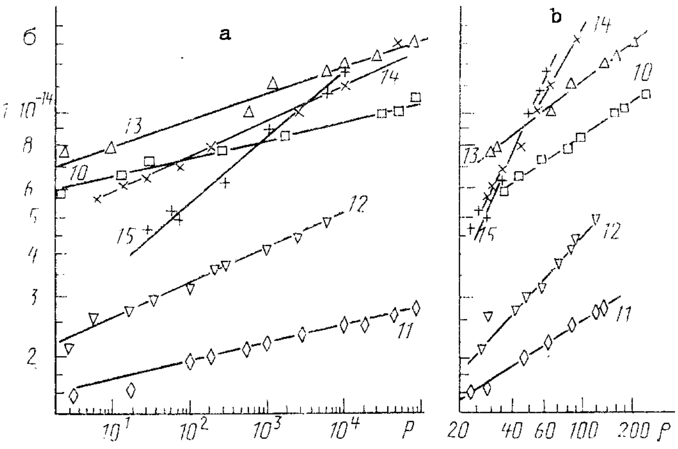

Fig. 4

Fig. 3. Dependence of the specific electrical resistance $r_e$, Ω·m$^2$ of glass fabric EVTI-7 on the compressive load $P$, Pa for a different number $n$ of layers.

Fig. 4. Dependence of the specific electrical conductivity $\sigma$, Ω$^{-1}$·m$^{-1}$ of VMI with PET-DA film shields on the load $P$, Pa (a) and stacking density $\rho$, cm$^{-1}$ (b): the numbers 10-15 correspond to Table 1.

(the magnitude of the exponent $k$ is taken from Table 1). The proportionality factor $A$ can be found if at least one value of $\lambda_{ef}$ is known for the appropriate insulation density $\rho$ obtained by the calorimetric method. By knowing $\lambda_{ef}$ and using the additivity rule, the contact heat conductivity coefficient can be found

$$\lambda_c = \lambda_{ef} - \lambda_r, \tag{4}$$

where $\lambda_p$ is determined by the optical properties [2, 3]. Substituting $\lambda_c$, $k$ and $\rho$ in (3), the magnitude of the factor $A$ can be found. The values of this factor for VPI and the data needed for its computation are presented in Table 2.

This approach permits a substantial reduction in the quantity of calorimetric measurements by replacing them with much more simple and rapid measurements of electrical quantities.

Computed dependences of the contact, radiation, and effective heat conductivity coefficients on the density are presented in Fig. 2 for pearlite, aerogel, and its mixtures with BPI. In conformity with [2], the assumption that the integral coefficient of total radiation attenuation by an insulation material is proportional to its density was used in the computation of the radiation conductivity coefficient.

It is seen from Fig. 2b that the increase in the contact conductivity as the insulation density (or its mechanical load) grows for the aerogel mixtures with BPI depends substantially on the metallic powder content in the mixture.

Thus, if an additional to the aerogel + 20 mass% BPI for $\rho = 200$ kg/m$^3$ does not alter $\lambda_c$ in practice, while an increase in the powder content to 40 mass% at the mentioned mixture density raises $\lambda_c$ by approximately 20%, then for $\rho = 250$ kg/m$^3$ and 20 and 40 mass% BPI contents, the $\lambda_c$ increases by 15 and 100%, respectively. Examination of the dependences of $\lambda_{ef}$ on $\rho$ shows the presence of a minimum that corresponds to the optimal density for this material, where as the metal powder content increases this optimum shifts towards lower densities.

Superposed for comparison in Fig. 2 are experimental dependences of $\lambda_{ef}$ on $\rho$ for aerogel and pearlite, obtained by the calorimetric method [4]. The sufficiently substantial divergence in the magnitude of the aerogel $\lambda_{ef}$ between the computed and experimental dependences is due to the fact that the latter is obtained for specimens having a heat conductivity coefficient 40% higher for $\rho = 100$ kg/m$^3$ than those for which the optical and electrical measurements were performed. The agreement is substantially better for pearlite. Attention is now turned to the difference in the nature of the dependences of $\lambda_{ef}$ on $\rho$ obtained in [4] by the calorimetric method and in this paper by using the results of optical and electrical measurements. This divergence becomes noticeable for densities 150-200 kg/m$^3$ and can be associated with degradation of the vacuum in the insulation as its density increases during the calorimetric measurements, as is indeed manifest in the more abrupt rise of the right branch of the experimental curves obtained in [4].

The presence of the optimum on the curves $\lambda_{ef}$—$\rho$ and its shift towards lower densities noted above as the content of the metallic powders shielding the thermal radiation increases is of substantial practical value. Utilization of aerogel mixtures with BPI with content of the latter elevated to 40-50 mass% is expedient for cryogenic vessels with rigid walls where the insulation experiences no mechanical loads. The insulation in vessels with flexible shells has a load of 1 kgf/cm$^2$ and the BPI content should be reduced to 20-25 mass%.

Dependences of the specific electrical resistance on the load are given in Fig. 3 for packets of the glass fabric EVTI-7 for a varying number of layers ($n = 1$-$20$). As is seen from the figure, an increase in the number of layers results in growth of the packet resistance over the whole load range. Surprisingly, the passage from one layer to another increases the specific resistance insignificantly. This is evidently because the addition of a second layer for a strongly rarefied glass fabric configuration results in an increase in the number of contacts with the boundary surfaces, and therefore, to a reduction in the resistance to compensate for the growth of this parameter due to the increase in the number of layers. For this reason, as well as because of magnification of the radiation interaction with the conductivity due to the increase in the quantity of material absorbing radiation between the shields, VMI with doubled interlayered materials has not found extensive practical application. However, such an approach may be justified in certain cases. It turns out that application of doubled interlayers in the insulation of large-scale tanks by vacuum-multilayer insulation with PET-DA film or aluminum foil shields and EVTI-7 glass fabric interlayers will contribute in the first case to loosening the insulation and improving its evacuation condition, and in the second case permits, in addition, a substantial decrease in the distance between adjacent shields because of local pressures during installation of the insulation and during cutting holes in it under supports, extensions, etc.

As the load grows, the packet resistance is lowered because of smoothing of the layers and the increases in the number of contacts between them. An increase in the number of layers in the packet, accompanied by an increase in its stiffness, results in the dependence of the resistance on the load becoming more shallow. Thus, the resistance is reduced 500 times in the load range $1 \cdot 10^{-6}$—1 kgf/cm$^2$ for $n = 2$ and 100 times in the same load range for $n = 20$.

The results obtained by the ETA (electrothermal analogy) method for pure powders and packets of fibrous sheet materials confirm the main regularities of heat transport over a solid body, disclosed earlier by using the calorimetric measurements [4]. This permits utilization of the ETA method to investigate contact heat transfer even in such a complex system as VMI.

Data on the specific electrical conductivity of different multilayer insulation compositions are shown in Fig. 4 as a function of the load on the specimen and the density of the insulation stacks described by expressions of the type (1). In conformity with the ETA the dependences for the contact thermal conductivity will also be described by analogous expressions, i.e.,

$$\lambda_c \sim P^m, \tag{5}$$

$$\lambda_c \sim \rho^t . \tag{6}$$

Values of the exponents in these formulas are given in Table 1.

As already mentioned, pressure of the insulation is accompanied by smoothing of the layers and an increase in the number of contacts between them. Consequently, the rate of growth of the contact conductivity as the load on the insulation increases is determined by the state of the surface of the layers making contact (smooth, nappy), their stiffness, the degree of rarefaction of the interlayers, etc.

It is seen from Table 1 that PET film and viscose-cellulose paper (No. 11) insulation is characterized by least sensitivity to pressure. Near it is also the composition with the glass fabric EVTI-7 (No. 10). The strongest growth of the contact conductivity with the load is detected when using the relatively stiff and elastic glass paper SBR as interlayer, especially in combination with shields from soft 10-μm-thick aluminum foil (Nos. 14 and 15). The dependence on the density for insulation with this interlayer material is similar in nature to a packet of sheet fibrous materials without shields (No. 9).

Lines 10, 13, 14 in Fig. 4b refer to VI compositions with PET film shields and interlayers of glass fiber materials. Comparison of these dependences shows that for small stacking densities the VMI with SBR-M-40 interlayers has the greatest efficiency. Close to it, although with a somewhat higher conductivity over a solid body for densities less than 35 $cm^{-1}$ is VMI with interlayers of the EVTI-7 glass fabric. These deductions are in good agreement with the results of calorimetric measurements and the experience of applying the mentioned compositions for Dewar vessel insulation.

It should be noted that the presence of complex radiation-conductive heat transfer in VMI, not subjected to the additivity rule, does not permit going over from qualitative regularities disclosed by the ETA method to a quantitative description of the dependence of contact conductivity on the load in this insulation.

An investigation of the dependence of $\lambda_{ef}$ of several VMI textures on a compressive load is performed by a calorimetric method in [5]. As in our paper, the measurements were performed for a constant number of layers and varying specimen thickness. The dependence

$$\lambda_{ef} \sim P^{0,43}$$

was obtained for insulation from PET-DA film and SBR-M-40 glass paper. Comparing it with the dependence (5) obtained for the same insulation by the ETA method shows that the former is substantially steeper. This can be explained by the fact that in the calorimetric measurements the pressure of the insulation results in growth of the heat flux through it not only because of the increase in contact conductivity but also because of the redistribution (equilibration) of the shield temperatures that governs the reduction of their efficiency and the increase in heat transport by radiation. The dependence (5) reflects the nature of the change of precisely the contact heat conductivity with the load. The deduction [5, 6] of the governing influence of the increase in contact conductivity on the growth of the effective VMI heat conduction coefficient as its thickness and density increases disproves the relatively weaker nature of the dependence of the VMI contact conductivity intrinsically on the load. Hence, the important practical deduction concerning the development of cryogenic vessels with flexible shells follows. There is no sense using VMI to insulate these vessels since its efficiency is reduced substantially for the reason elucidated above. This deduction is confirmed by comparing the results of measuring the $\lambda_{ef}$ of VMI with PET film shields and interlayers of basalt and polymer fibers [7] and of isotropic insulation from ultrathin glass fiber (this paper). Both kinds of insulation had $\lambda_{ef}$ = 16 μW/(cm·K) after pressure by a 0.1 MPa load.

Therefore, investigations by the ETA method have confirmed the main heat transfer regularities in VPI and VFI discovered earlier by a calorimetric method. They showed that the dependence of the intrinsically contact conductivity on the load for VMI is weaker than that from calorimetric measurements and permitted empirical dependences to be obtained that afford the possibility of performing qualitative and, in a number of cases (for VPI and VFI), also quantitative estimates of the contribution of contact conductivity to the total heat transport through insulation. The results obtained are used for the development of flat-walled cryogenic chambers with flexible shells for the storage of biological materials in liquid nitrogen.

## NOTATION

Here $\sigma$ is the specific electrical conductivity; $r_e$, specific electrical resistance, $\rho$, bulk density and the density of insulation stacking, $\lambda$, coefficient of heat conduction; $k$, $m$, and $t$, exponents; $A$, proportionality factor; $P$, compressive load; and $n$, number of layers. Subscripts: $ef$ is effective, $c$, contact, $r$, radiation.

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# EFFECT OF HEAT LOSSES FROM THE SURFACE OF A TWO-LAYER SPECIMEN ON MEASUREMENT OF THERMOPHYSICAL CHARACTERISTICS BY THE PULSED METHOD

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*The errors introduced by heat losses from a plate surface are estimated by comparing the solution of the heat propagation problem in a two-layer system with action of a pulsed heat source on one side in the presence of radiant heat exchange at the outer surfaces of the plate with the solution of the same problem for adiabatic boundary conditions.*

The appearance in construction and technology of new synthetic materials with unknown thermophysical properties demands use of highly productive procedures for study of the latter. Among such techniques are pulsed methods, which permit determination of thermal diffusivity and thermal conductivity coefficients as well as specific heat of a film coating deposited on a base with known thermophysical characteristics.

The pulse method for determining thermophysical characteristics of coatings described in [1] assumes thermal insulation of the specimen surface on both sides, which is impossible to accomplish completely, even for measurements in a vacuum.

The present study will establish temperature limits for use of the pulse method for determining thermophysical characteristics of coatings deposited on a base. The theoretical basis of this method is solution of the heat propagation problem in a two-layer plate upon action of a pulsed radiation source on the coating surface (Fig. 1). Using generally accepted assumptions the problem can be described by the following system of equations:

$$\frac{\partial T_1}{\partial \tau} = a_1 \frac{\partial^2 T_1}{\partial x^2}, \quad 0 \leqslant x \leqslant l_1, \tag{1}$$

$$\frac{\partial T_2}{\partial \tau} = a_2 \frac{\partial^2 T_2}{\partial x^2}, \quad -l_2 \leqslant x \leqslant 0, \tag{2}$$

$$\lambda_1 \left( \frac{\partial T_1}{\partial x} \right)_{x=l_1} = Q\delta(\tau) - g_{l_1}, \tag{3}$$

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