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EXPERIMENTAL INVESTIGATION OF THE GAS PERMEABILITY OF SHIELD-VACUUM HEAT INSULATION

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This is an experimental and theoretical study of the longitudinal and transverse permeability to gas of screen-vacuum heat insulation.

The level of vacuum and the intensity of molecular heat transfer in layers of shield-vacuum heat insulation (SVHI) are determined both by its gas separation and its permeability to gas, which has been studied extremely insufficiently, both theoretically and experimentally [1-4].

The present work reports on the experimental study of the effect of the structure of shields and interlayers (riffled, crumpled, corrugated, type of perforation, diameter of fibers, thickness, and porosity) and of the density of packing of the layers of SVHI on its longitudinal and transverse permeability to gas in the molecular regime of gas flow and on the verification of the possibility of describing it theoretically on the basis of the diffusion model. The diffusion approach to the description of molecular flows was suggested by

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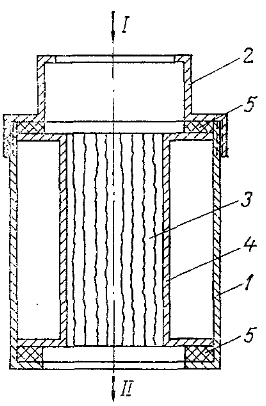

Fig. 1

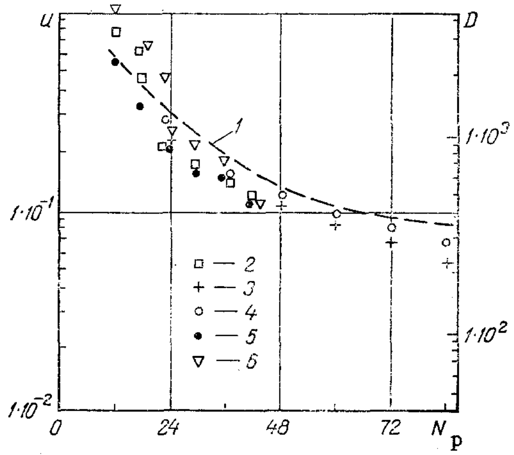

Fig. 2

Fig. 1. Diagram of the cassette for investigating longitudinal permeability to gas of SVHI: 1) cassette housing; 2) sleeve nut; 3) specimen; 4) sleeve for holding specimen; 5) gaskets; I) gas flow; II) to evacuation.

Fig. 2. Dependence of the conductivity of SVHI on the packing density of the layers in the longitudinal direction: 1) theoretical curve; 2) crumpled screens; 3) crumpled screens and glass-fiber reinforced paper SBSh-T; 4) crumpled screens and basalt paper NT-10; 5) glass-fiber reinforced paper SBSh-T; 6) basalt paper NT-10. D, cm²/sec; u, liters/cm²·sec; N_p, cm⁻¹.

TABLE 1. Characteristic of Shields and Gaskets of SVHI

Serial No.	Designation and composition of material*	Weight of 1 m², g	Thickness, μm	Mean diam. of fibers, μm	Porosity, %
1	Film PÉT DA perforated	18	12	—	1—3
2	Glass-fiber paper SBSh-T	7	26	0,4—0,6	89
3	Glass-fiber paper SBShS-T	8	30	0,6	89
4	Basalt paper NT-10 (B = 75%, C = 25%)	45	25	0,6	87
5	Basal paper (B = 80%, C = 20%)	150	400—450	0,74	85
6	Glass-fiber paper SBR-M	12	60	5—7	92,5
7	Glass-fiber canvas ÉVTI-7	4,8	25	12	92,3

* B = basalt; C = cellulose.

Clausing [5] and theoretically rigorously substantiated solely for long circular and flat channels and isotropic porous media [6, 7]. This approach was also used for stacks of SVHI [8] but there is as yet no rigorous experimental verification of the applicability of the diffusion approach to the description of the process of evacuation of anisotropic porous media of the type of SVHI.

Experimental Investigations. The permeability to gas of SVHI longitudinally and transversely was determined on an installation [4] by the method of constant pressure in molecular regime of gas flow.

In the transverse direction permeability to gas was studied on a stack of SVHI with 55 mm diameter. The thickness of the stack could be changed by gaskets from 0.5 to 6 cm, and the packing density from 12 to 150 screens/cm.

For investigating longitudinal permeability to gas, the specimens were made in the form of a flat multilayer rectangular stack (36 × 45 × 18 mm) along which dry nitrogen was blown during the experiment. The packing density in this case varied between 12 and 42 screens/cm. A diagram of the cassette with a specimen for determining longitudinal permeability to gas is shown in Fig. 1.

TABLE 2. Longitudinal Permeability to Gas of Stacks of SVHI (packing density 36 layers/cm, length of stack 45 mm)

No. of exp.	Composition of stack	Conductivity, liters/sec·cm²	Diffusion coeff., cm²/sec
1	Basalt paper NT-10 as supplied	0,18	810
2	Glass-fiber reinf. paper SBSh-T as supplied	0,16	720
3	Crumpled PET DA	0,14	630
4	Crumpled PET DA + basalt paper	0,146	658
5	Crumpled PET DA + SBSh-T as supplied (fleecy)	0,162	730
6	Smooth PET DA + SBSh-T as supplied (fleecy)	0,12	540
7	Crumpled PET DA + SBSh-T after treatment preventing fleeciness	0,192	865
8	Film PET DA, riffled on a grid 5×5 mm + basalt paper NT-10	0,165	743
9	Smooth NT-10 + corrugated (corrugations perpendicular to evacuation)	0,189	850
10	Smooth PET DA + corrugated NT-10 (corrugations perpendicular to evacuation)	0,180	810
11	Smooth NT-10 + corrugated PET DA (corrugations perpendicular to evacuation)	0,046	205
12	Smooth PET DA + corrugated (corrugations perpendicular to evacuation)	0,034	152
13	Smooth NT-10 + corrugated PET DA (corrugations along evacuation)	0,264	1190
14	Smooth PET DA + corrugated NT-10 (corrugations along evacuation)	0,274	1230
15	Smooth NT-10 + corrugated (corrugations along evacuation)	0,207	933
16	Smooth PET DA + corrugated (corrugations along evacuation)	0,203	915
17	Basalt paper (δ_i = 0.45 mm, $\bar{\rho}_i$ = 19.5 layers/cm)	$1,78\cdot10^{-2}$	80,5
18	PET DA + basalt paper 0.45 mm thick (N_p = 39 layers/cm)	$1,49\cdot10^{-2}$	67

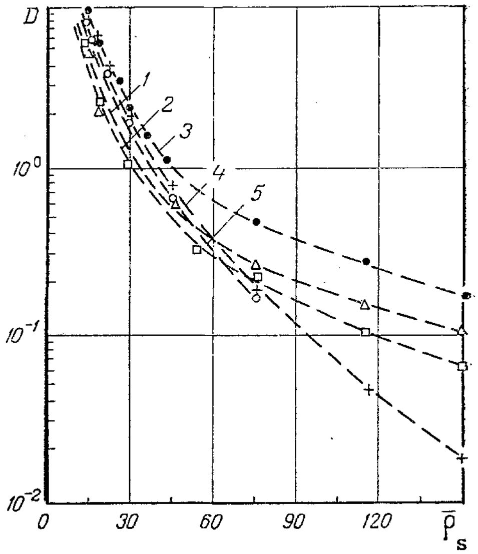

Fig. 3. Dependence of the diffusion coefficient of SVHI in the transverse direction on the packing density of the screens: 1) film PET, P_s = 4.14%, d_s = 2 mm, and glass-fiber reinforced paper SBSh-T; 2) film PET, P_s = 3.14%, d_s = 2 mm, and basalt paper NT-10 (B = 75%, C = 25%); 3) film PET, P_s = 3.14%, d_s = 2 mm, and glass fiber canvas EVTI-7; 4) film PET, P_s = 3.14%, d_s = 2 mm; 5) theoretical curve. D, cm²/sec; $\bar{\rho}_s$, cm⁻¹.

The experiments were carried out with pressures in the range $10\text{-}10^{-2}$ Pa, and the total error of determining permeability to gas did not exceed ±20%.

We investigated two-component (on the basis of shields and gaskets) and single-component (on the basis of only one kind of gaskets or shields) composites whose principal characteristics are presented in Tables 1-3.

Longitudinal permeability to gas of SVHI is shown in Fig. 2 and Table 2, transverse one in Fig. 3 and Table 3.

Diffusion Model. Longitudinal and transverse permeability to gas of stacks of SVHI with porous screens (perforated and diffraction screens) can be described by one universal relation [9]

TABLE 3. Transverse Conductivity of SVHI 1 cm Thick

No.	Characteristic of stack	Stacking density, layers/cm	Conductivity, liter/sec·cm²	Diffusion coefficient cm²/sec	
				expt.	calc.
1	Basalt paper (δ_i=0.4 mm, B=80%, C=20%)	15	$1.6\cdot10^{-2}$	16	12,3
2	The same	22	$1.35\cdot10^{-2}$	9,4	8,4
3	Basalt paper as in No. 1 + DDE (P_s = 6.3%)	15+15	$7.2\cdot10^{-3}$	7,2	5,2
4	The same	22+22	$6.4\cdot10^{-3}$	4,5	3,8
5	Basalt paper as in No. 1+ perforated screens (P_s = 1%)	15+15	$1.4\cdot10^{-3}$	1,4	0,72
6	The same	22+22	$5.1\cdot10^{-4}$	0,35	0,28
7	Glass-fiber paper SBSh-T	18	0,115	115	145
8	Basalt paper NT-10	18	0,114	114	82
9	Glass-fiber paper SBR-M 40	18	0,48	480	500
10	Glass-fiber canvas ÉVTI-7	18	1,37	1370	1680
11	Perforated screens 2 × 10 mm (P_s=3.14%)	18	$7.6\cdot10^{-3}$	7,6	7,65

$$D = \frac{1}{3} V_a L_D, \quad u = \frac{D}{l}, \tag{1}$$

where the structure of the stack of SVHI in the direction of evacuation is described with the aid of the characteristic dimension L_D. The parameter L_D is equal to the mean free path of the gas molecules (up to the collision with the gasket or the screen) in their motion along or across the stack of SVHI. The relations for calculating L_D are presented in Table 4; they are obtained on the basis of the results of [9], and for transverse gas flow through SVHI from perforated screens we used a modified expression from [2].

In writing the relations 3, 5, 6 in Table 4 we assumed that the gaskets of microthin glass or basalt fibers, in view of the small probability of free electrons passing through them, $\alpha_i \ll 1$, play in SVHI the part of an impermeable wall for the longitudinal gas flow. Therefore in determining the width of the channel, we took into account the screens as well as the gaskets. As a result the introduction of such gaskets is bound to reduce longitudinal permeability to gas of SVHI with free stacking of the layers.

Results of the Experimental and Theoretical Investigation. It can be seen from Fig. 2 that the dependence of longitudinal permeability to gas u of SVHI and of the diffusion coefficient D on the packing density of the layers is not only of the same nature for all composites from the investigated insulating stacks, but that the absolute values are also close to each other, and these, in turn, are close (within the limits of a factor of 1.5-2) to the theoretical curve: dependence 1 and relation 1 in Table 4. This confirms the conclusion that gaskets types SBSh-T and NT-10 act as impermeable walls to the longitudinal gas flow in SVHI.

Some scatter of the experimental points about the theoretical curve is due to the change of permeability of SVHI on account of the crumpling of the screens, whose positive or negative effect is connected with the directivity of the lines of crumpling in relation to the direction of evacuation. This conclusion is confirmed by the data of Table 2, which presents the results of investigations of SVHI with smooth and corrugated screens and gaskets (width of the corrugations 5 mm, packing density 36 layers/cm) when the SVHI is evacuated along and across the corrugation. Almost all the composite SVHI with longitudinal corrugation (except 3, 6) have conductivity (0.15-0.18 liter/cm²·sec) close to the theoretical value 0.195 liter/cm²·sec. When the corrugations coincide with the direction of evacuation, it increases the conductivity of SVHI by a factor of 1.2-1.5 (experiments 13-16), and when they are arranged transversely, it reduces permeability to gas by a factor of 3-4 but not to zero (experiments 11, 12).

Longitudinal permeability to gas of stacks of SVHI on the basis of corrugated packing materials may differ by between 10 and 50%, depending on the direction of the corrugations (experiments 9, 15 and 10, 14). This shows that gaskets of thin fibers are much less permeable in the direction normal to their surface than the gap between adjacent layers is.

The experiments (Table 2) showed that longitudinal permeability to gas of SVHI is somewhat lower when not smooth but fleecy gaskets type SBSh-T are used. In insulation

TABLE 4. Characteristic Dimension L_D for Different SVHI

Direction of evacuation	No. of relation	Composition and structure of stack	Characteristic dimension
Along the stack	1	Crumpled, smooth, riffled screens	$L_D = 2\bar{\rho}_s^{-1}$
	2	Smooth, crumpled, riffled gaskets (thin and compact ones)	$L_D = 2\bar{\rho}_i^{-1}$
	3	Screens alternating with gaskets (compact) or one kind of gasket	$L_D = \bar{\rho}_s^{-1} - \delta_i$
	4	Layers between screens completely filled by gaskets	$L_D = \dfrac{2}{\bar{\rho}_s + \dfrac{2}{\delta_i}}$
	5	Gaskets packed without gaps	$L_D = \dfrac{\alpha_i \delta_i}{1 - \alpha_i}$; $\alpha_i = \dfrac{d_f \rho}{d_f \rho + m}$
	6	Thick gaskets with gaps	$L_D = 2(\bar{\rho}_i^{-1} - \delta_i)$
Across the stack	7	Gaskets without gaps	$L_D = \dfrac{\alpha_i \delta_i}{1 - \alpha_i}$; $\alpha_i = \dfrac{d_f \rho}{d_f \rho + m}$
	8	Gaskets with gaps	$L_D = \dfrac{\alpha_i}{1 - \alpha_i} \bar{\rho}^{-1}$
	9	Perforated screens; perforated screens+gaskets with $\alpha_i \approx 1$ (type ÉVTI-7)	$L_D = \dfrac{\alpha_s}{1 - \alpha_s} \bar{\rho}_s^{-1}$; $\alpha_s = \dfrac{3}{4} P_s \alpha_0$
	10	Perforated screens+gaskets	$L_D = \dfrac{\bar{\rho}_s^{-1}}{\dfrac{1 - \alpha_i}{\alpha_i} + \dfrac{1 - \alpha_s}{\alpha_s}}$
	11	Perforated screens+gaskets with $\alpha_i \ll 1$	$L_D = \dfrac{3}{4} \dfrac{1}{\bar{\rho}_s} \dfrac{P_s}{1 + \dfrac{3\pi d_s^2 \ln \dfrac{t\sqrt{2}}{d_s}}{32\left[(\delta_s - \delta_i)^2 + \dfrac{1}{2}\delta_i^2\right]}}$

stacks consisting of two components the decrease of longitudinal permeability to gas on account of the surface of the gaskets amounted to 15% (experiments 5, 7), and in combination with crumpled or smooth screens to 30% (experiments 3, 6).

It follows from Fig. 3 and Table 3 that the experimental data on transverse permeability to gas of perforated PET film P_s = 3.14% in dependence on the packing density is in good agreement with the theoretical values of [10]. The diffusion relation 10, Table 4, describes this dependence (curve 5 in Fig. 3) if the probability α_0 of the passage of molecules through a layer of two screens is taken from the data of [10], which were calculated by the Monte Carlo method.

It should be noted, however, that with packing densities above 20-40 1/cm transverse permeability to gas of composites from perforated screens and gaskets differs greatly from the values obtained on the basis of the diffusion model (relation 11, Table 4), which takes into account the longitudinal resistance of two gaps between a gasket and the adjacent screens (for gaskets types NT-10 and SBSh-T with $\alpha_i \ll 1$) or the gap between screens (for gaskets types ÉVTI-7 $\alpha_i \approx 1$) at the distance t between adjacent holes, the resistance of these holes, and the transverse resistance of the gasket. The experimentally found permeability to gas of composites with gaskets in the range of densities above 20-40 screens/cm decreases more slowly than in stacks with equal perforated screens, and when the density is even greater, the permeability to gas is greater than that of equal screens. Further increase of density to 150 screens/cm reduces the permeability to gas of a stack with gaskets very slightly; this permeability settles at an almost unchanged level which, in dependence on the type of gasket, differs by a factor of 1.5-2. It follows from Fig. 3 that this asymptotic level is determined by the conductivity of the gasket material itself, and therefore for composites with gasket NT-10 it is lower than with gasket SBSh-T (Fig. 2), and it is maximal for composites with gasket ÉVTI-7. Hence follows that with high packing densities transverse permeability to gas of a stack of SVHI with gaskets is already determined by the resistance of the holes in the screens and by the resistance of the material of the gaskets.

NOTATION

U, specific permeability of gas; D, diffusion coefficient; $V_a = \sqrt{8RT/\pi M}$, mean thermal velocity of molecules; T, temperature; R, universal gas constant; M, molecular weight; L_D, mean path length of molecules up to collision with surfaces of SVHI; δ, distance between adjacent layers of SVHI; ℓ, thickness of a stack of SVHI: ρ_i, packing density of gaskets; P_s, porosity of a screen; d_f, mean diameter of fibers in a gasket; d_s, diameter of a hole in the screen; ρ, density of the material of the fibers; α_s, α_i, probability of passage of molecules through the screen and gasket, respectively; m, weight of 1-m^2 gasket; δ_i, thickness of the gasket; ρ_s, packing density of screens; α_0, probability of passage of molecules through a single layer [10]; δ_s, thickness of a screen; N_p, stacking density of layers of gaskets and screens; t, distance between holes.

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INVESTIGATION OF THE STRUCTURAL AND HYDRAULIC PROPERTIES OF CAPILLARY POROUS MATERIALS FOR HEAT PIPES

G. V. Kuskov and Yu. F. Maidanik

UDC 536.27

The article analyzes the principal requirements regarding the properties of capillary porous materials for wicks of antigravitation heat pipes. Their porosity, coefficients of permeability and sinuosity are determined.

In the analysis of processes of heat and mass transfer in heat pipes, information on the properties of the capillary porous materials (CPM) used in them is of importance. On the

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