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EXPERIMENTAL STUDY OF THE THERMAL AND GASDYNAMIC PROPERTIES OF INSULATION WITH PERFORATED DIFFRACTING SCREENS

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An experimental study is made of the thermal, optical, and gasdynamic characteristics of a new cryogenic thermal insulation.

The reduction in the radiative and contact components of heat flow in vacuum-shield thermal insulation (VSTI) attained by improving the properties of the materials of the screens and interlayers has made it possible to improve the characteristics of VSTI's only up to a certain point. As was shown in [1-3], a further improvement in the effectiveness of VSTI's is related to the need to reduce heat transfer by gas molecules in their layers. In a first approximation, the pressure of the gases p_g in the layers of porous VSTI's is described by the relation [4]

$$p_g \approx \frac{W_0(\delta - x)^2}{2D}. \tag{1}$$

It follows from Eq. (1) that one of the most promising methods of reducing the pressure is increasing the gas permeability of the VSTI packets. The perforated VSTI screens presently used for this purpose do not reduce gas pressure in the layers of the VSTI to the required level without an accompanying significant increase in radiant heat transfer [5, 6]. However, as was shown in [7], if the size of the holes in the metal screen is made less than half the wavelength of the incident thermal radiation, then the resulting diffraction screen, even with a porosity of about 90%, will be impermeable to radiation but at the same time permeable to the gas molecules. It follows from the theory in [7] that for cryogenic heat insulation the holes in the screens should be no larger than 2.5 μm. If the diffraction screens are made on the basis of metallized polymer films, then the thickness of the metallic coating in the channels should be close to the thickness of the metallized layer comprised of the outer surfaces of the screen.

The authors of [8] proposed the use of metallized nuclear filters as perforated diffraction screens (PDS). Such filters are obtained through the action of accelerated heavy ions,

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TABLE 1. Effective Emissivity of VSTI Shields (T = 310°K)

Number	Type of shield	Material of coating	Diameter of holes d, μm	Porosity p, %	Effective emissivity ε_e
1	PDS	Aluminum	2—2,5	10—12	0,28—0,36*
2	PDS	»	1—2	3—7	0,09—0,11†
3	PDS	»	0,6—0,65	8	0,044
4	PDS	»	1,0	10	0,046
5	Without holes	»	—	0	0,029—0,032
6	Smooth perforated	»	2000	3,14	0,05
7	Smooth perforated	»	1000	8	0,13
8	Fluted perforated	»	2000	3,14	0,07—0,12
9	PDS	»	0,74	3—5	0,033—0,036
10	Without holes	Copper	—	0	0,024
11	PDS	»	0,65	3—4	0,033
12	Without holes	Silver	—	0	0,015
13	PDS	»	0,65	3—4	0,02

*Specimen not subjected to ultraviolet radiation during manufacture.

†Thickness of layer of metal on surface of channels in the PDS less than 0.005 μm.

such as argon or xenon nuclei, on 5-20-μm-thick polymer films followed by ultraviolet irradiation of the material and chemical etching of damaged sections of the film [9, 10]. This technology was developed in the Joint Institute of Nuclear Research in Dubna and makes it possible to manufacture nuclear filters of sufficient mechanical strength with porosities up to 20% and a pore-diameter dispersion no greater than 4%. These filters have the properties of a perforated diffraction screen after they are metallized.*

Presented below are results of a study of the optical and gasdynamic characteristics of PDS's made on the basis of nuclear filters and the thermal conductivity of VSTI's with diffraction screens.

Emissivity of the PDS. The experimental unit in [11] was used to study the optical properties of the PDS. Table 1 presents results of a comparison of the effective emissivity† ε_e of different types of shields at a temperature of 310°K. It is apparent from the data that the emissivity of a PDS from the first-made batch (specimens Nos. 1 and 2) is considerably greater than that of shields without holes. To determine the reason for this deterioration, we studied the effect of the direct transmission of heat radiation through the holes in a PDS on the value of ε_e with a change in the emissivity of the bounding walls. These tests, as later measurements‡ made with an infrared spectrometer of the permeability of perforated screens to heat radiation with wavelengths of 1-10 μm, showed that there was no transmission and that the deterioration in the emissivity of the PDS is related to other factors.

In particular, values $\varepsilon_e = 0.28\text{-}0.36$ were typical of the specimens not subjected to ultraviolet radiation before the etching operation. In this case, attempts to deposit a sufficiently thick layer of metal on the walls of the channels in the PDS were unsuccessful since the channels in such screens vary widely in dimensions, are complex in cross section, and have a rough surface. It is well known that when the thickness of the metallic layer is small, radiation can penetrate almost freely through this layer [12] and be absorbed in the volume of the film substrate of dielectric material.

Strong absorption of radiation entering the channels is equivalent to an increase in the emissivity of the PDS. Thus, in the future it will be necessary to include ultraviolet irradiation of the film polymer before its etching in the production process for the PDS.

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*The metallization of sample nuclear filters has been mastered by the special design office for vacuum coatings in Riga.

†By the effective emissivity of the PDS, we mean the emissivity of a solid shield which could be substituted for the PDS in a system without changing radiant heat transfer in the system.

‡The measurements were made by A. I. Zvyagin and V. I. Kut'ko, staff members at the Physicotechnical Institute of Low Temperatures.

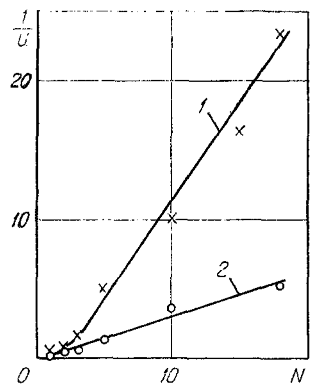

Fig. 1

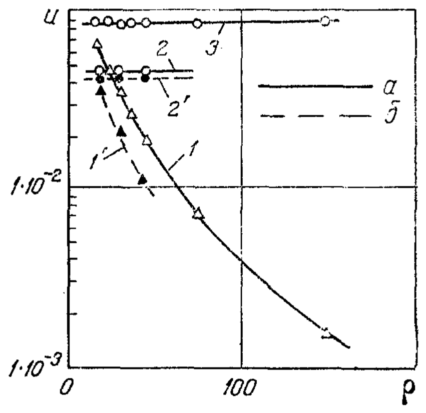

Fig. 2

Fig. 1. Dependence of the unit resistance of a packet of insulation on the number of layers (1/u, $m^2 \cdot sec/m^3$): 1) perforated screens with 2 × 10 mm holes (p = 3.14%); 2) PDS, p = 9%, d = 0.5 μm, δ_{fm} = 8 μm.

Fig. 2. Dependence of the permeability of a VSTI on the packing density, N = 18 shields (u, $m^3/m^2 \cdot sec$, ρ, 1/cm): 1, 1') VSTI based on fluted perforated screens, p = 3.14%, d = 2 mm; 2, 2') VSTI based on PDS, p = 3-4%, d = 0.6-0.7 μm; 3) VSTI based on PDS, p = 9%, d = 0.5 μm; a) interlayers of VSTI-7 glass-film; b) interlayers of SBSh-T glass-paper.

Improvement of the metallization technology increased the thickness of the metallic layer inside the channels to 0.01-0.015 μm (with a thickness of 0.04-0.06 μm for the coating itself), which has made it possible to obtain values of effective emissivity of the PDS (ε_e = 0.033-0.036) near the values of ε_e of the shields without holes (ε_e = 0.029-0.032). Even lower values of emissivity have been obtained on nuclear filters coated with copper and silver (specimens 11 and 13).

It follows from analysis of the data in Table 1 (specimens Nos. 5-8) that perforation of the shields leads to a substantial increase in ε_e and, thus, to a substantial increase in radiant heat transfer in the VSTI. Thus, perforated screens with a porosity greater than 3% are not used in practice. At the same time, it follows from the completed experiments (Table 1) that the use of diffraction screens makes it possible to increase the porosity of insulation shields up to 10% without any significant deterioration in the radiative characteristics.

Permeability of a PDS. One of the main parameters determining the gas pressure in the layers of the insulation is its permeability. The permeability of a PDS to nitrogen or air in the molecular flow regime through a specimen was determined by the method of constant pressure in the pressure range $10-1 \cdot 10^{-2}$ Pa. The unit we developed in [13] and the measurement method permitted tests of both individual shields and of packets of insulation up to 60 mm thick with specimens 45 mm in diameter.

The experiments showed that metallization of a perforated film with holes from 0.6 to 1 μm in diameter leads to a negligible decrease in the permeability of the original material. For example, the permeability of a film with a porosity of 4.8-5% and holes 0.74 μm in diameter was $1 \cdot 10^{-2}$ $m^3/m^2 \cdot sec$ before metallization and $9.2 \cdot 10^{-3}$ $m^3/m^2 \cdot sec$ after the vacuum deposition of an aluminum layer 0.05 μm thick. However, the permeability of a perforated film may be markedly reduced after metallization if the diameter of the holes is reduced.

One feature of insulation with diffraction screens is that the gasdynamic resistance of the insulation increases in direct proportion to the increase in the number of screens (Fig. 1). This is due to the fact that the distance between the channels is many times less than the distance between the individual screens, and most of the resistance to the motion of the gas is exerted by the channels themselves.

This principle does not hold for conventional perforated insulation, since resistance becomes proportional to the thickness of the insulation packet only when there is a large number of screens — because of the effect of the hydraulic resistance of the gaps between

TABLE 2. Permeability of VSTI's (N = 18, ρ = 18 shields/cm)

Insulation	Diameter of holes d, μm	Porosity p, %	Permeability u, $m^3/m^2 \cdot sec$
Conventional perforated	2000	3,14	$(3{,}5-5)\cdot 10^{-2}$
Perforated diffraction	0,7	2,7	$(1{,}6-3{,}6)\cdot 10^{-2}$
	0,74	5	$5{,}1\cdot 10^{-2}$
	0,7	8	$9{,}6\cdot 10^{-2}$
	1,2	11	$(15-22)\cdot 10^{-2}$
	0,7	15	$14{,}3\cdot 10^{-2}$
	0,9	20	$24\cdot 10^{-2}$

the screens. Thus, in contrast to the case of a conventional perforated insulation, the gas permeability of a PSD will be determined only by the number of screens and should not depend on the density with which the layers are arranged when packed together to values $\rho \sim 500$ screens/cm, i.e., when the distance between the screens is commensurate with the distance between the holes in them. The completed experiments (Fig. 2) confirmed the above conclusion. In the entire range investigated (from 18 to 150 screens/cm), the permeability of the PDS-based insulation remained unchanged, while for the insulation with 3% perforation an increase in packing density led to a reduction in the permeability of the specimen by a factor of 50.

As the experiments showed, porous interlayer materials have almost no effect on the permeability of insulation based on perforated diffraction screens. Thus, to improve the efficiency of the VSTI it appears that it would be possible to use optically denser interlayers, such as interlayers based on glass-paper made of microscopic fibers, without appreciably lowering the permeability of the VSTI. The introduction of similar interlayers into conventional perforated insulation would significantly reduce its permeability, particularly with an increase in packing density (Fig. 2).

It follows from Fig. 2 that, with free packing and the same porosity (3%), perforated and diffraction insulation have roughly the same permeability. The permeability of the former cannot be increased appreciably, since 3% of porosity is the maximum permissible value from the point of view of radiant heat transfer. The porosity of PDS-based insulation, on the other hand, can be increased to 10-20% without significantly increasing radiant heat transfer. This makes it possible to increase the gas permeability of the VSTI by a factor of 3-10 (Table 2).

The completed experiments also showed that gas evolution from the perforated screens is lower than from the solids shields formed under identical conditions. This fact, along with the higher permeability of the PDS to nitrogen, ensures a lower pressure in the layers of the diffraction insulation than in the VSTI with conventional perforated screens.

Thermal Conductivity of Insulation with Diffraction Screens. To evaluate the efficiency of the new insulation, we performed comparison tests of three variants of VSTI with packet thicknesses from 5 to 60 mm on an experimental calorimetric unit with a cylindrical vessel with a volume of 14 liters. The following commercial vacuum-shield insulations were used in the tests:

1) insulation with nonperforated crumpled shields with one-sided aluminum-coating ($\varepsilon_e \approx 0.05$) and without interlayers;

2) insulation with fluted perforated screens with a two-sided aluminum coating (porosity 3.14%, $\varepsilon_e \approx 0.1$) and interlayers of VSTI-7 glass-film (fiber diameter 8-13 μm, weight 7 g/m²).

To compare results of tests of diffraction and perforated insulations, it is best if they have the same porosities and gas permeabilities. To this end, we prepared a batch of perforated diffraction insulation with a porosity of 3-4%, holes 0.6-0.7 μm in diameter and $\varepsilon_e = 0.045-0.047$ (deposition of copper or aluminum on two sides). The interlayers used were made of SBSh-T fiber-paper (fiber diameter 0.4-0.6 μm, weight 8 g/m²).

The above insulations were studied in the temperature ranges 290-77 and 290-20.4°K. The results are shown in Fig. 3. As can be seen, the insulation with the diffraction screens had a thermal conductivity 1.3-1.5 times lower in all of the tests than the commercial VSTI

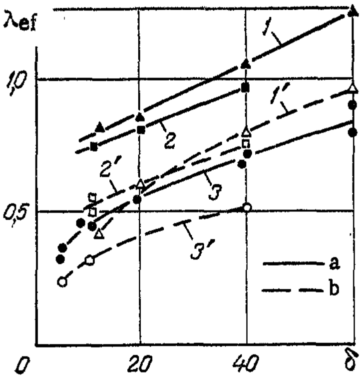

Fig. 3. Comparison of the thermal conductivity of VSTI (λ_{ef}, W/cm•K, δ, mm): 1, 1') VSTI made of crumpled PETF (polyethylene terephthalate) film with one-sided aluminum coating, no holes, ρ = 16 shields/cm; 2, 2') VSTI made of fluted perforated screens, p = 3.14%, d = 2 mm, ρ = 16 screens/cm; 3, 3') VSTI based on PDS, p = 3-4%, d = 0.6-0.7 μm, ρ = 19 screens/cm; a) range of boundary temperatures 300-77°K; b) 300-20.4°K.

compositions. If we compare the conventional perforated and diffraction insulations, we can attribute the resulting difference to the better optical characteristics of the PDS, since the gas permeabilities of the insulations are nearly the same.

The greater efficiency of the perforated insulation compared to the nonperforated variants is the result of a reduction in gaseous heat transfer. If we analyze the reasons for the reduction in heat flux with a reduction in the temperature of the cold wall from 77 to 20.4°K, we see that the heat flux to the liquid nitrogen and hydrogen changes negligibly (within 10%) for each thickness of diffraction insulation. At the same time, this difference in heat fluxes for the nonperforated insulation increase from 2 to 35% with a reduction in packet thickness from 60 to 12 mm. Thus, gaseous heat transfer is considerably lower in the diffraction insulation than in the nonperforated insulation. Considering that the PDS production process is such that the gas permeability of the VSTI can be increased appreciably, it might be expected that gaseous heat transfer can be almost eliminated in such a structure.

Both the PDS-based insulation and the other VSTI's exhibit a dependence of the thermal conductivity on the thickness, although it is less pronounced. One possible reason in this case is the increase in contact conductivity with an increase in the thickness of the insulation due to its compaction during winding.

The following conclusions can be made as a result of the study.

A technology has been developed for making perforated diffraction screens for VSTI's. A study was made of the optical and gasdynamic properties of PDS's and insulation packets based on them. It was established that the emissivity of a PDS is significantly lower (by a factor of two to three) than the emissivity of conventional perforated screens of the same porosity and is close to the emissivity of similar solid screens. It was also found that, given the same porosity and free laying of the layers, the gas permeability of PDS packets is roughly the same as that of conventional perforated screens. We determined that the gas permeability of PDS packets remains unchanged with an increase in packing (laying) density from 18 to 150 screens/cm. This is in contrast to the case of packets of conventionally perforated VSTI's, in which gas permeability decreases by a factor of fifty. Thanks to their combination of good optical and gasdynamic properties, PDS's are the most promising type of shield for low-temperature and cryogenic technologies.

Heat-engineering tests of the new perforated diffraction insulation on a model vessel with liquid nitrogen and hydrogen showed that its thermal conductivity is 1.3-1.5 times lower than that of serially produced thermal insulations used in cryogenic technology.

The new type of VSTI can be recommended for broad practical application in cryogenic systems. Considering the high thermal efficiency and improved gas permeability of the new VSTI, the most promising areas of its application should be systems which require a maximum reduction in weight and heat flow through the thermal protection, which use VSTI packets of substantial thickness, or which require maximum acceleration of the evacuation process.

NOTATION

p_g, pressure; W, rate of gas evolution per unit volume; δ, thickness of the insulation; x, running coordinate; D, diffusion coefficient; d, diameter of holes; ε_e, effective emissivity of surface shield; p, porosity; u, unit permeability; ρ, packing (laying) density; δ_{fm}, film thickness; N, number of shields; λ_{ef}, effective thermal conductivity.

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