NOTATION

λ_1, λ_2, λ_3, coefficients of thermal conductivity along the x, y, and z axes; a_1, a_2, and a_3, coefficients of thermal diffusivity along the x, y, and z axes; c_V, volume heat capacity; v, velocity of the heat source and temperature sensor; and q, power of the heat source.

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EFFICIENCY OF "SHIELDLESS" METHOD OF EMPLOYING THE COLD OF VAPORS IN CRYOGENIC VESSELS WITH A WIDE NECK

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Methods for raising the efficiency of cryobiological vessels with liquid nitrogen are proposed and realized, and a method for calculating their heat-shielding is developed and tested.

Theoretically [1] the full utilization of the cold of vapors enables reducing by a factor of 1.6-1.7 the flow of heat into small vessels with liquid nitrogen. Most often, for this purpose a large number of radiation shields are placed on the cold neck [2]. This construction is difficult to realize and labor-consuming, its mass is large, and for a number of reasons (small number of shields, decrease in the effective length of the neck, increase in the emissivity of the shields owing to cryogenic deposits, etc.), it does not permit full use of the cold of the vapors. The method of placing heat shields within a packet of screen-vacuum thermal insulation (SVTI), cooled with a drainage pipe [3], is less complicated but less efficient.

In small vessels the full utilization of the cold of vapors can be achieved with the help of a simple "shieldless" method, when all SVTI layers are cooled with the drainage neck, along which they are stretched over the entire length and have a good "thermal" contact with it. The shieldless method is employed in serially produced Kh-34B cryobiological vessels [4], but it has not been adequately tested theoretically and experimentally. This is primarily a result of the fact that there are no experimental data and methods for calculating the components of the heat inflow into the vessel with the indicated construction taking into account the thermal interaction of the SVTI packet and the drainage neck.

The purpose of this work is to test experimental and computational methods for evaluating the components of the heat inflow taking into account the use of the cold of vapors and developing recommendations with regard to their efficiency. The components of the heat inflow (with and without the use of the cold of the vapors) along the neck, its plug, and vapors of the cryogenic component were determined experimentally from their thermal conductivity and the temperature gradient in the lowest cold layers of these elements (5-7 mm thick), found with the help of differential thermocouples. The decrease in the temperature gradient in each element (including also in SVTI) owing to the use of the cold of the vapors determines the efficiency of the "shieldless" method of cooling. The thermal conductivity of the

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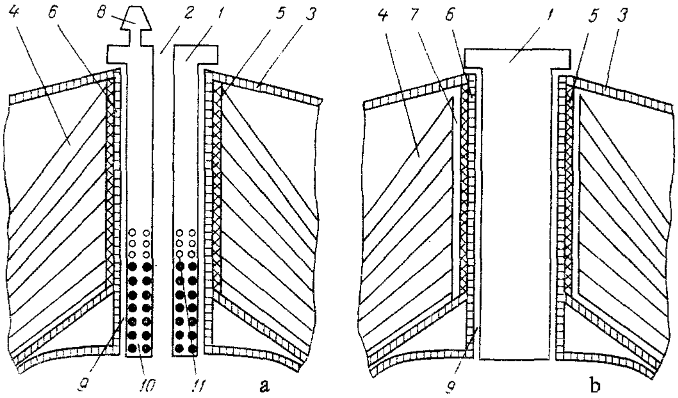

Fig. 1. Diagram of the Kh-34B vessel: a) the insulation packet is in contact with the neck; b) there is a gap between the insulation packet and the neck; 1) plug; 2) central channel in the plug; 3) outer housing; 4) SVTI layers; 5) glass paper layers; 6) fiberglass neck; 7) vacuum gap between SVTI layers and the necks; 8) vacuum stopper; 9) gas gap between the neck and the plug; 10) zeolite; 11) perlite.

SVTI packet in different modifications of the Kh-34B cryogenic vessel was determined from the data obtained on the heat inflow through the different elements and the evaporability of the vessel.

Six modifications of the vessel were prepared in order to change experimentally the degree of utilization of the cold of vapors from the minimum (~0) to the theoretically maximum (~1.7) levels; 1) a serially produced vessel with a polystyrene plug; 2) the vessel 1 with a 2-3 mm gap between the SVTI and the plug; 3) vessel 1 with a glass evacuated plug; 4) vessel 3 with a gap at the neck; 5) vessel 3 with central openings in the plug for escape of vapors; and, 6) vessel 5 with a gap at the neck.

In vessel 1 a good contact was provided between the SVTI packet and the neck along its entire length and maximum utilization of the cold of vapors was obtained, while in vessel 6 vapor utilization was reduced to almost zero. The glass plug, the central opening in it for vapors (or escape of vapors along the gap at the neck), and the gap between the SVTI and the neck in vessels 2-6 made it possible to regulate to a different extent the degree of utilization of the cold of vapors in SVTI, the neck, and the plug. The serially produced vessel 1 had an effective polystyrene plug (the diagrams of the polystyrene and glass plugs are shown in Fig. 1). To reduce the transverse thermal conductivity of the plug it was replaced in the experiments with vessels 3-6 by a glass plug (with a wall 1.5 mm thick), filled with a vacuum-powder thermal insulation based on finely dispersed perlite. In addition 80 g of zeolite NaX absorbent was placed in the cold zone of the plug. Prior to being poured into the plug the absorbent was heated for 1.5 days up to a temperature of 600 ± 10 K. After sealing and cooling a vacuum of 0.2 Pa was achieved in the plug; after liquid nitrogen was poured into the vessel the vacuum was improved by another 1.5 orders of magnitude. Vapor from the vessel was passed along the gap between the plug and the neck (2 mm thick, like in the serially produced vessel) or through a central opening 1-2 mm in diameter. In this case the gap between the neck and the plug was sealed with a dense layer of glass paper with glue, and also additionally covered in the warm zone.

The Kh-34B cryogenic vessel and the technology employed to fabricate it are described in [4, 5]. The insulation (based on a film of PÉT-DA 5 μm thick and ÉVTI-7 glass papers) were deposited by a machine method in the form of ribbons 8-9 cm wide. The neck of the vessel had a diameter of 60 mm (the working length equalled 210 mm and the thickness equalled 1.2 mm) and was made of fiberglass. Its outer surface was coated with seven layers of ÉVTI-7 glass papers prior to the installation of the SVTI. When the SVTI were installed copper—constantan thermocouples were placed along their thickness, along the layers, the neck, and the plug [4, 5].

In experiments with vessels 2, 4, and 6 the gap between SVTI and the neck was formed as follows: four cylindrical segments 4 mm thick and 30 mm high were placed around the neck at the bottom. After the SVTI were installed up to a height of 20-25 mm the segments were

TABLE 1. Results of the Thermal Calculations of Different Modifications of the Kh-34B Vessel

Element of vessel	Modification of vessel	Magnitude of heat inflow, W			Utilization degree of vapors cold	Effective SVTI coeff., μW/(cm·K)	
		calc.(absence of vapor)	expt.	calc. (cold vapors)		expt.	calc.
Vessel as a whole	1	0,57	0,35	0,38	1,5		
	2	0,57	0,47	0,43	1,33		
	3	0,67	0,42	0,47	1,43		
	4	0,67	0,57	0,52	1,29		
	5	0,67	0,60	0,61	1,10		
	6	0,67	0,66	0,67	1,0		
SVTI	1	0,36	0,25	0,25	1,44	0,93	1,34
	2	0,36	0,38	0,34	1,06	1,43	1,34
	3	0,36	0,23	0,25	1,44	0,85	1,34
	4	0,36	0,38	0,34	1,06	1,42	1,34
	5	0,36	0,32	0,28	1,29	1,21	1,34
	6	0,36	0,39	0,35	1,03	1,46	1,34
Polystyrene plug	1	0,06	0,03	0,03	2		
	2	0,06	0,03	0,02	3		
Fiberglass neck	1	0,14	0,06	0,09	1,56		
	2	0,14	0,06	0,06	2,3		
	3	0,14	0,06	0,10	1,4		
	4	0,14	0,05	0,08	1,75		
	5	0,14	0,11	0,16	0,88		
	6	0,14	0,11	0,15	0,93		
Glass plug	3	0,16	0,14	0,11	1,45		
	4	0,16	0,14	0,09	1,78		
	5	0,16	0,16	0,16	1,0		
	6	0,16	0,16	0,16	1,0		

raised and the installation of the SVTI and raising of the segments were repeated in succession.

The experimental data on the total heat inflows and their components are given in Table 1, while Figs. 2 and 3 show the curves for the temperature distribution in the neck and SVTI (along and across). The working model of the heat transfer in the Kh-34B vessel is also given below. Heat transfer through SVTI is described by the two-dimensional heat-condition equation

$$\frac{\partial}{\partial r}\left(r^2\lambda_r(T_{\mathrm{i}})\frac{\partial T_{\mathrm{i}}}{\partial r}\right)+\frac{1}{\sin\Theta}\frac{\partial}{\partial\Theta}\left(\sin\Theta\lambda_\theta(T_{\mathrm{i}})\frac{\partial T_{\mathrm{i}}}{\partial\Theta}\right)=0, \tag{1}$$

in the plug

$$\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho\lambda_\rho(T_{\mathrm{p}})\frac{\partial T_{\mathrm{p}}}{\partial\rho}\right)+\frac{\partial}{\partial z}\left(\lambda_z(T_{\mathrm{p}})\frac{\partial T_{\mathrm{p}}}{\partial z}\right)=0, \tag{2}$$

and by the one-dimensional heat-conduction equation in the neck and in the gas column:

$$\frac{d}{dx}\left(\frac{\lambda_{\mathrm{n}}(T_{\mathrm{n}})+\lambda_{\mathrm{g3}}(T_{\mathrm{n}})}{F_{\mathrm{n}}+F_{\mathrm{g3}}}\frac{dT_{\mathrm{n}}}{dx}\right)+\frac{C_p\dot{m}}{F_{\mathrm{n}}+F_{\mathrm{g3}}}\frac{dT_{\mathrm{n}}}{dx}=\frac{q_s(T_{\mathrm{n}})S}{F_{\mathrm{n}}+F_{\mathrm{g3}}}. \tag{3}$$

The temperature dependence of the thermal conductivity of these elements is described by the single equation $\lambda(T) = \sum_{i=0}^{3} a_i T^i$ [6], while the values of a_{i} are presented in [1]. Heat transfer between the SVTI packet and the neck (through the layer of glass paper) is described by the equation [7]

$$q_s=\frac{\lambda_{\mathrm{gp}}(T_{\mathrm{i}}-T_{\mathrm{n}})}{\delta_{\mathrm{gp}}}+\varepsilon\sigma(T_{\mathrm{i}}^4-T_{\mathrm{n}}^4)\Big/\left(1+\frac{3}{4}\varepsilon\tau_0\right). \tag{4}$$

This equation is valid for a layer of a purely scattering medium with a good contact between this layer and the boundaries. In the absence of such a contact (experiments with vessels 1, 3, and 5) the first term in Eq. (4), describing heat transfer by heat conduction along the framework of the solid body, equals zero.

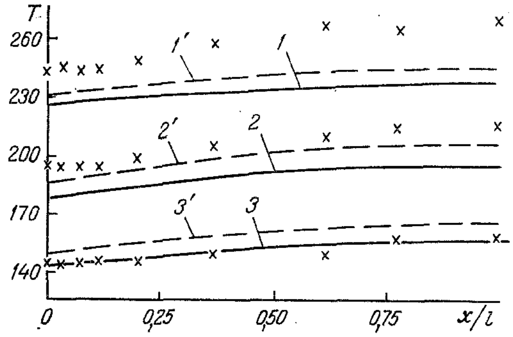

Fig. 2. Variation of the temperature along the insulation layer, starting at the neck, for different sections along its thickness: 1) temperature of the layer at a height of 0.53δ from the vessel; 2) 0.3δ; 3) 0.15δ; the broken curves are explained in Fig. 3.

Equations (1)-(3) were solved by an iteration method using Liebman's method [8]. The temperature distributions in adiabatic SVTI and in the neck (the latter taking into account cooling by its vapors [6]) was used as the first approximation. The values of the parameters λ_{gp} and τ_0 were taken from the experimental data [9] on the temperature dependence of the effective thermal conductivity of ÉVTI-7 glass paper for different values of the emissivity of the boundaries. For one layer of ÉVTI-7 glass paper we have $\tau_0 = 0.31$, for seven layers $\tau_0 = 2.17$, and the transverse thermal conductivity of the glass paper equals

$$\lambda_{gp}(T) = 5.51\cdot 10^{-5} - 2.33\cdot 10^{-7}T + 5.35\cdot 10^{-9}T^2 + 1.55\cdot 10^{-11}T^3. \quad (5)$$

The results of calculations of the heat inflows are given in Table 1; the temperature distributions in SVTI and the neck are shown in Figs. 2 and 3. In all variants the heat inflows along the gas column did not exceed 0.01 W, while the heat inflows along the gap between SVTI and the neck were less than 0.02-0.03 W, so that they are not given in the table. The smallness of the heat transfer along the gap (less than 5-10% of the total heat inflow) is indicated by a comparison of the heat inflows to vessels 5 and 6 (Table 1). This is due to the very large elongation of the gap, $\ell/\delta_{ins} \geq 100$ (the length equals 210 mm and the thickness equals 2-3 mm). It also follows from the experimental and computed data for vessels 5 and 6 (0.61, 0.60 W and 0.67, 0.66 W, respectively) that in these vessels it was indeed possible to eliminate almost completely the use of the cold of the vapors. The minimum value corresponds to vessel 6 with a gap between SVTI and the neck, while in vessel 5, where these elements are in contact, the cold of the vapors partially (by approximately 15%) reduces the total heat inflow.

In vessels 2, 4, and 6 the absence of contact between the SVTI and the neck (and the decrease in the use of the cold of the vapors) increases the heat inflows by 20-30%. In the presence of such a contact (through the layer of glass paper) in vessels 1 and 3 (with both glass and polystyrene plugs) the total heat inflow is reduced by a factor of 1.5. From here it follows that 91% of the cold of the vapors is employed in these vessels, i.e., it is almost completely utilized. Thus the formation of a good contact between the SVTI packet and the neck along its entire length [1] is one of the most important problems in designing and fabricating cryogenic vessels.

It should be noted that the coupling between the end of the SVTI and the neck by a purely radiant pathway through a layer of scattering material of the ÉVTI-7 type (vessels 2, 4, and 6 with a gap between SVTI and the neck) turns out to be inadequate and for this reason the total heat inflow increases appreciably, since the vapors cool only the neck of the vessel. This degradation equals about 30%, and taking into account the longitudinal radiative heat transfer along the gap, even 40%. For this reason, when SVTI are mounted on vessels of the Kh-34B type, gaps at the joint with the neck are not permissible, and the SVTI packet must be stretched over the entire length of the neck and be in good thermal contact with it along a special layer of glass film or glass paper. With this implementation of small vessels the "shieldless" method enables full utilization of the cold of the vapors.

In order to perform calculations it is necessary to have data on the effective thermal conductivity of the SVTI packet directly on the vessels. For this purpose the experimental

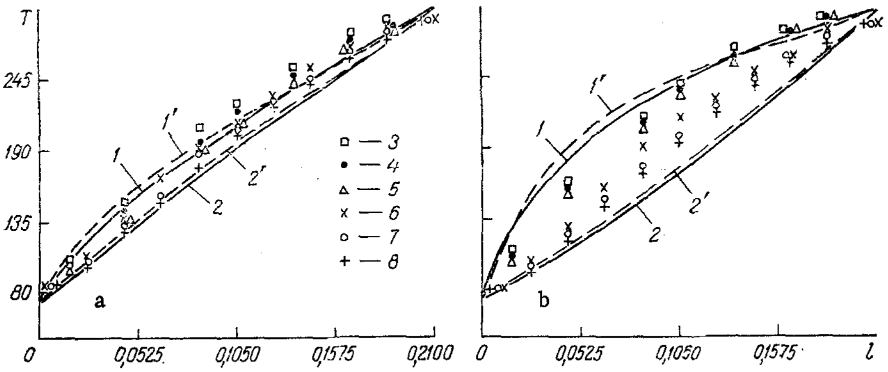

Fig. 3. Temperature profiles along the thickness of the insulation and along the neck for vessels in which the SVTI is in contact with the neck (a) and for vessels which have a gap between the SVTI packet and the neck (b): 1, 1') computed temperature profiles of SVTI for a vessel with a polystyrene plug; 2, 2') computed temperature profiles of the neck; the broken curves show the calculation for the experimental values of $\lambda_r(T)$ for an SVTI packet; 3, 4, 5) experimental values of the temperature of SVTI at the joint with the neck for vessels 6, 4, 2 (a) and 5, 3, 1 (b), respectively (see Table 1); 6, 7, 8) experimental values of the temperature of the neck in the same vessels.

results (1.43, 1.42, and 1.46 µW/(cm·K)) for vessels 2, 4, and 6, in which cooling owing to the vapors was practically excluded, can be used. It is only necessary to take into account the fact that these data include the additional heat inflow along the gap between the SVTI and the neck. According to the calculations, this quantity equals about 8%, and for this reason the thermal conductivity of the SVTI in the calculations is assumed to equal 1.34 µW/(cm·K) for all six modifications of the Kh-34B vessel. As follows from Table 1, this unified approach describes well the experimental data (within 5-12%) both on the total heat inflow and its components for vessels 2, 4, and 6 and for vessels 1, 3, and 5 (in which the cold of the vapors is substantially employed). The value obtained for the thermal conductivity of SVTI λ_r = 1.34 µW/(cm·K) is the average integrated value for the temperature range 77-300 K and SVTI thickness varying from 40 mm (central part of the vessel) to 210 mm at the neck (the average thickness of the packet equals 70 mm). This value agrees satisfactorily with the experimental data [11] for the experimental vessel with liquid nitrogen with a volume of 14 liter (λ_r = 1.2 µW/(cm·K) for a thickness of 80 mm).

The calculation based on the foregoing method taking into account the two-dimensional temperature distribution in the SVTI requires information not only about the average integrated thermal conductivity of the SVTI but also about its temperature dependence. In this work the character of the temperature dependence of this parameter was taken from the data of [12], increased at all points by a factor of 2.3 in order to obtain the mean integrated value λ_r = 1.34 µW/(cm·K). It is obvious from Table 1 that this approach describes well the total heat inflows and their components for all six modifications of the vessel. At the same time it is obvious from Figs. 2 and 3 that the longitudinal and transverse temperature profiles in the SVTI and the neck are not described as well. For example, along the SVTI only the temperature profile at the cold wall is described accurately; in the transverse temperature profile the points near the cold and the warm walls are described correctly, while at the center the discrepancy between experiment and calculations reaches 5-15 K. This discrepancy is attributable to the fact that because of the significant heat transfer along the gas the variation in the thermal conductivity over the thickness of the SVTI is nonmonotonic and has a maximum at the center of the SVTI packet. This distribution of the thermal conductivity can be found approximately from the experimentally determined transverse temperature profile under the assumption that the heat flux along the thickness of the SVTI is constant and the thickness itself is constant:

$$\lambda_r(T) = 3.8\cdot 10^{-5} + 4.59\cdot 10^{-7}T - 7.76\cdot 10^{-9}T^2 + 3.81\cdot 10^{-11}T^3 \text{ for } T < 260,$$
$$\lambda_r(T) = -2.04\cdot 10^{-2} + 2.16\cdot 10^{-4}T - 7.41\cdot 10^{-7}T^2 + 8.29\cdot 10^{-10}T^3 \text{ for } T > 260. \quad (7)$$

One can see from Figs. 2 and 3 that the temperature profiles obtained based on this dependence are already appreciably closer to the experimental profiles. The dependences (7) were also used to determine the total heat inflows and their components for vessels 1-6. It turns out that to within the limits of accuracy of the calculation they are identical to the computed results already presented in Table 1. Two fundamental results follow from the foregoing.

1. The exact change in the thermal conductivity as a function of the temperature is not significant for the calculation of the total heat inflows and their components in cryogenic vessels of the type Kh-34B; only its average integrated value over the temperature and thickness of the SVTI is important.

2. A more accurate description of the temperature profiles in the elements of the thermal shielding of cryogenic vessels requires more accurate data on the character of the temperature dependence of their thermal conductivities.

The investigations performed also showed that the main paths for improving the Kh-34B cryogenic vessels are as follows: reducing the thermal conductivity of the neck material (for Kh-34B vessels its contribution equals 20-25%); development of more efficient SVTI compositions (its contribution equals 60-70%); the use of special heat treatment of SVTI, heating it up to the thermoplastic state in order to reduce the contact heat transfer [10]; and, increasing the vacuum in the SVTI layers in order to eliminate heat transfer along the gas.

NOTATION

T, temperature; λ, thermal conductivity, F, area; x, z, r, ρ, and Θ, coordinates along the axis of the neck and plug, along the thickness of the SVTI and plug, and along the SVTI layers, respectively; δ, thickness of the SVTI packet; λ_{gp}, thickness of the layers of glass paper on the neck; ε, emissivity; σ, Stefan–Boltzmann constant; C_p, heat capacity of the vapors of the cryogenic agent; m, flowrate of the vapors from the vessel; ℓ, length of the neck; a, a constant; τ_0, optical thickness of the glass papers; S, area of the lateral surface of the neck; q_s, specific heat flux through the layers of glass papers; δ_{ins}, width of the gap between SVTI and the neck. Indices: n, neck; g, gas; p, plug; i, screen-vacuum thermal insulation; and gp, glass paper.

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