DETERMINING AND ELIMINATING FACTORS IMPAIRING THE EFFICIENCY OF CRYOGENIC VESSELS

G. G. Zhun', V. F. Getmanets, V. A. Miroshnichenko, and V. I. Shalaev

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The substantial influence of liquid-nitrogen vaporization from Kh-34B vessels on cryogenic precipitates, the coating of screens with an adsorbent dust, and the destruction of the intermediate SVTI material has been experimentally established. Methods are proposed and have been tested to eliminate the effects of these factors on vaporization.

The requirements imposed on the effective functioning of commercially produced cryogenic vessels increase from year to year; therefore, the question of ascertaining, studying, and eliminating those factors which reduce their serviceable life is quite urgent. In particular, based on experiments, vaporization from Kh-34B-type cryogenic vessels increases with time and changes from vessel to vessel (within limits of 15-25%). In this connection, in the present study, using commercially produced Kh-34B cryogenic vessels with liquid nitrogen, we have experimentally studied the change in their efficiency under a variety of operational conditions: the formation of a cryogenic precipitate on the cold screens of screen-vacuum thermal insulation (SVTI), the "blackening" of SVTI layers with particles of a carbon adsorbent, and the destruction of SVTI-7 frosted glass during heat treatment.

For purposes of the experiments we fabricated four vessels (Nos. 1-4) of the Kh-34B type, using the technology described [1, 2]. The assembly of the SVTI (PET-DA screens 5 μm thick and SVTI-7 frosted glass) was accomplished with an orbital machining method involving a strip 90-100 mm in width. Prior to the assembly of the SVTI, the frosted glass was subjected to preliminary heat treatment at a temperature of 80-100°C for a 24-h period. Vessels Nos. 1-4 were subjected to prolonged thermal degasification at a temperature of ~90°C involving evacuation and heating in one segment of an electric furnace. For purposes of controlling the temperature fields, temperature sensors (copper-constantan thermocouples) were mounted in vessels Nos. 1, 2, and 4 along the throat and transverse sections of the SVTI. For this same reason, a zone approximately 7 cm thick was selected in the SVTI which served as the mean integral quantity for the SVTI packets in the Kh-34B vessels.

Vessels Nos. 1-3 (with an identical initial vaporization of ~124 g/day) were designated for purposes of evaluating the extent of cryogenic precipitation, gas release, and destruction of the SVTI-7 frosted glass during the heat treatment. For this very reason, an additional amount of AAUT-type fabric treated with activated carbon was added in vessel No. 3 on the cold wall (1.2 × 0.3 m in size, and a mass 0.5 kg), while this adsorbent in vessel No. 2 was equally divided between two layers of the SVTI at a distance of 0.25 and 0.5 of the SVTI thickness from the inner vessel.

Vessel No. 4 (vaporization ~150 g/day) is used to study the influence of SVTI screen "blackening" by means of application of dustlike adsorbent particles on the efficiency of the vessel. Activated charcoal of mass 0.3 kg is poured into the aluminum cavity around the throat of the vessel; this activated carbon contained 70-80% particles smaller than 1 mm. For the control vessels Nos. 1-3 this fraction of the carbon was initially screened. Vessels Nos. 1-4 were heated in air (with a closed evacuation valve) to a temperature of ~90°C, and then the air was suddenly evacuated to the atmosphere from the insulated cavities of these vessels. This caused carbon dust to be thrown into the SVTI layers in vessel No. 4.

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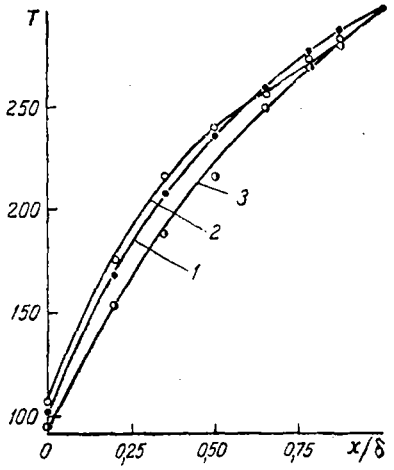

Fig. 1

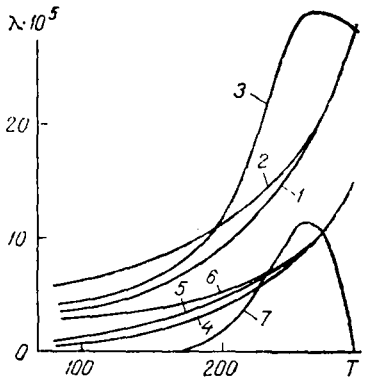

Fig. 2

Fig. 1. Temperature T, K, as a function of reference thickness x/δ of dimensionless SVTI: 1) vessels Nos. 1 and 2 for τ = 10 days and vessel No. 2 for τ = 180 days; 2) vessel No. 1 for τ = 180 days; 3) vessel No. 4 for τ = 10 days.

Fig. 2. Temperature (T, K) dependent change in the effective coefficient of SVTI thermal conductivity $\lambda \cdot 10^5$, W/(m·K) and its components: 1) λ_{eff} for vessel No. 2 (τ = 10 and 180 days) and No. 1 (τ = 10 days); 2) λ_{eff} for vessel No. 4; 3) λ_{eff} for vessel No. 1 (τ = 180 days); 4) λ_{rad} for vessel No. 2 (τ = 10 and 180 days) and No. 1 (τ = 10 days); 5) λ_{rad} for vessel No. 4 (τ = 180 days); 6) λ_{rad} for vessel No. 4; 7) λ_g for vessel No. 1 (τ = 180 days)

TABLE 1. Thermal Characteristics of Kh-34B Vessels after Establishment of Steady-State Regime (1) and after a Lapse of Half a Year (2)

Vessel No.	Vaporizability g/day		Heat flux, W	
	1	2	1	2
1	125	149	0,279	0,33
2	122	125	0,273	0,279
3	124	146	0,294	0,323
4	150	—	0,344	—

In addition to the temperature fields, we also monitored vaporization gravimetrically (with an accuracy of ±4%): in vessel No. 4 we measured the initial vaporization (at τ = 10 days), while in vessels Nos. 1-3 we measured the vaporization both initially and after a period of half a year (see Fig. 1 and Table 1).

We can see from Table 1 that the initial vaporization in vessels Nos. 1-3 is virtually identical. For vessel No. 4 the vaporization is greater by ~20%, which is a result of the change in the optical properties of the SVTI screens under the action of the carbon dust. In vessels Nos. 1 and 2 the temperature fields during the initial period of the experiments are also identical (τ = 10 days, see curve 1 in Fig. 1). In vessel No. 2 the vaporization virtually underwent no change over a period of half a year (less than 2%), whereas in vessels Nos. 1 and 3 it increased by 17-18%. Nor was there any change in the temperature profile in vessel No. 2 over half a year; this profile exhibits a monotonic nature without any bends. These facts indicate an absence in vessel No. 2 of noticeable heat transfer through the gas as a consequence of the effective functioning of the adsorbent placed in the middle of the SVTI packet [1-3].

In vessels Nos. 1 and 3 after a lapse of half a year the vaporization increased by 17-18%, and the temperature curve showed a break (in the zone of ~255 K), so that the temperatures in the hot SVTI zone dropped, while increasing in the cold zone. According to the conclusions of [3], this gives evidence of the elevated gas pressure in this SVTI zone. Hence it follows that the displacement of even an excess quantity of adsorbent only at the cold wall of the vessel makes it impossible to maintain the required vacuum for any length of time within SVTI layers more than 70 mm in thickness.

The validity of this conclusion as well as the role of other heat-transfer components in the SVTI can also be evaluated from the shape of their temperature curves. For determination of these relationships, we will divide the cross section of the SVTI in which the thermocouples are mounted into elementary segments of thickness $\Delta\delta$. The effective coefficient of thermal conductivity $\lambda_{eff}(T)$ for any i-th segment can then be determined from the Fourier equation:

$$\lambda_{\text{eff}}(T) = q\Delta\delta/\Delta T. \tag{1}$$

In the SVTI section under consideration, with the mean integral thickness, the specific heat flow q is also equal to its mean value for the vessel. As we used Eq. (1) we also bore in mind the increase in the transverse flow of heat from the cold to the warm wall (by a factor of up to two), caused by its partial removal along the SVTI layers to the throat section and through it to the vapors of the cryogenic agent. The function q(T) was found with the method described in [4]. The error in the determination of the coefficient $\lambda_{eff}(T)$ amounted to 9-13%, and its relationship to temperature for vessels Nos. 1, 2, and 4 is shown in Fig. 2 (curves 1-3).

For vessel No. 1 on curve 3 (after half a year) we find a maximum at T = 250-260 K, which is caused by local heat transfer through the gas to the SVTI. For vessel No. 2 and for vessel No. 1, at the initial instant of time (τ = 10 days) we note a monotonic nature for the change in the function $\lambda_{eff}(T)$ (curve 1), which is analogous to the relationship derived earlier with a plane calorimeter [5]. In the SVTI of these vessels there is no transfer of heat through the gas and the heat transfer is therefore accomplished by radiation through the solid:

$$\lambda_{\text{eff}}(T) = \lambda_{\text{rad}}(T) + \lambda_{\text{con}}(T). \tag{2}$$

Radiant heat transfer can be calculated by means of the following equation [6] (see Fig. 2, curve 4):

$$\lambda_{\text{rad}} = 4\frac{\varepsilon}{2-\varepsilon}\frac{\delta}{N}\sigma T^3, \tag{3}$$

where the emissivity ε was taken from the data of [5]. Then, from relationship (2) we determine $\lambda_{con}(T)$ (see Fig. 3, curve 1). It follows from the data of Figs. 2 and 3 that for all temperatures the transfer of heat through the solid predominates over that due to radiation, and on the average its contribution amounts to 56%.

The solid component of $\lambda_{con}(T)$ (Fig. 3, curve 1) may be assumed to be identical for all vessels (Nos. 1-4), considering the identity of the SVTI, the techniques for its assembly, and the heat treatment. For purposes of comparison Fig. 3 (curve 3) shows also the function $\lambda_{con} = \lambda_{con}(T)$, obtained with a plane calorimeter [6]. We see that at a temperature of 80-200 K these relationships are similar in nature, but differ in magnitude approximately by a factor of 1.5. At temperatures above 200 K, in the SVTI of Kh-34B vessels, we observe a sharp increase in the component $\lambda_{con}(T)$. This increase may be caused by the additional increase in radiant heat exchange $\Delta\lambda_{rad}$ in the SVTI layers because of a combination of the following factors.

A change in the color of the SVTI-7 layer is observed in the outer SVTI layers (from colorless to yellow-brown) during the process of subjecting the SVTI to vacuum heat treatment. Moreover, as the layers are heated the SVTI adhere to each other because of the softening of the PVA glue used in fabricating the SVTI-7 frosted glass. The elevated level of contact heat exchange in combination with the increase in the absorption capacity of the yellowing SVTI-7 intermediate layer leads to an increase in the radiant heat exchange within the SVTI [7, 8]. The quantity $\Delta\lambda_{rad}$ is equal to the difference in the values of curves 1 and 2 (Fig. 3). Curve 2 represents the purely contact component. Let us assume that in the region 80-200 K the addition $\Delta\lambda_{rad} \approx 0$, while the quantity λ_{con} is proportional to the

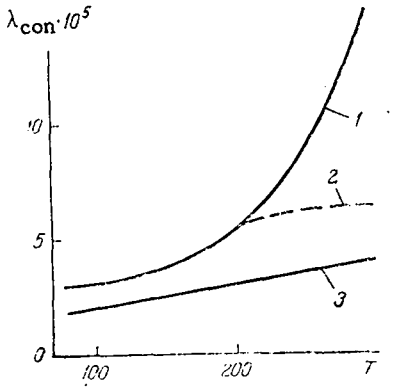

Fig. 3

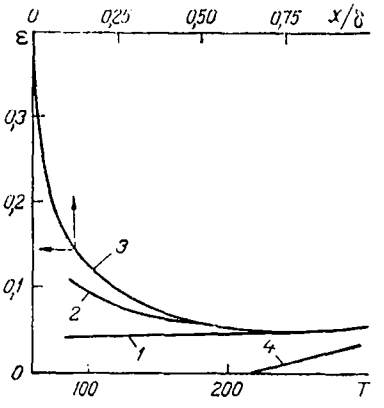

Fig. 4

Fig. 3. Relationship between temperature T, K, and the conductive SVTI heat-transfer component $\lambda_{con} \cdot 10^5$, W/(m·K): 1) $\lambda_{con} + \Delta\lambda_{rad}$ for vessels Nos. 1-4; 2) λ_{con} for vessels Nos. 1-4; 3) λ_{con} for plane calorimeter with SVTI packing density of 16 screens/centimeter.

Fig. 4. Emissivity ε in SVTI layers as a function of temperature, dimensionless and varying over SVTI thickness x/δ: 1) calorimetric data for screens [5]; 2) ε in the presence of a cryogenic precipitate in vessel No. 1 (τ = 180 days); 3) ε when SVTI layers are blackened with coal dust; 4) change in ε for SVTI layers by altering the color of SVTI-7 frosted glass.

thermal conductivity of the glass. Extrapolating the function $\lambda_{con} = \lambda_{con}(T)$ to the region 200-300 K along the curve for the thermal conductivity of the glass, we obtain curve 2 (Fig. 3). The quantity $\Delta\lambda_{con}$ from Eq. (1) also gave us the change in the emissivity of the SVTI layers (due to the change in the color of the frosted glass), as shown by curve 4 in Fig. 4.

In order to verify the conclusion to the effect that the destruction of the SVTI-7 frosted glass significantly affects the conductive-radiative exchange of heat in the SVTI, we performed additional experiments with three identical Kh-34B vessels [1, 2], in which the frosted glass exhibited various levels of destruction. The colorless frosted glass in these experiments was subjected to preliminary heat treatment at temperatures of 380-400 K for various periods of time until it achieved a cream or brown color. As a result of these tests, we found the following vaporization quantities for the vessels: 130, 155, and 176 g/day, respectively, for the colorless (without heat treatment), the cream-colored, and the brown frosted glass.

On prolonged utilization of vessel No. 1 (τ = 180 days), without an adsorbent in the middle of the SVTI, the screen emissivity within the vessel becomes impaired because of the desublimation of the water vapor which makes up 70-90% within the products of gas evolution [9]. The change in the radiant component that is due to the cryogenic precipitate is determined from the difference between the values of curves 3 and 1 (see Fig. 2) in the region 80-180 K, where the partial water vapor pressure is less than the pressure in the SVTI (p = 10^{-2}-10^{-3} Pa). Based on this difference, from Eq. (3) we have determined the addition to the screen emissivity, and its resulting value is shown in Fig. 4 (curve 2). This curve has subsequently been extrapolated to the calorimetric data with respect to ε (curve 1) [5]. It follows from curve 2 that for low values of temperature the value of ε exceeds the values for the screens without cryogenic precipitate by a factor of 2-3.

We used curve 2 (Fig. 4) and Eq. (3) also to determine the temperature relationship for the radiant heat exchange in vessel No. 1 after half a year of operation (Fig. 2, curve 5). The difference between the values of λ_{eff}, λ_{rad} (Fig. 2, curves 3 and 5), and λ_{con} (Fig. 3, curve 1) yields a value for the transfer of heat through the gas in vessel No. 1 after half a year (Fig. 2, curve 7). It follows from Fig. 2 that the transfer of heat through the gas significantly affects only the SVTI layers at temperatures of 190-290 K and in this region they are comparable to other components of heat transfer.

Let us now turn to an examination of radiant heat exchange in vessel No. 4. We will determine its magnitude (Fig. 2, curve 6) by eliminating from the total value of λ_{eff} (Fig. 2, curve 2) the transfer of heat through the solid λ_{con} (Fig. 3, curve 1). From the value of curve 6 (Fig. 2), taken from Eq. (3), we find the change in the emissivity of the layers through the thickness of the SVTI, caused by the blackening with coal dust (Fig. 4, curve 3). We see that the coal dust penetrates to a relative depth of up to 0.5, while at a depth of 0.1 the emissivity increases by a factor of as much as 3-10. Let us note that the preliminary screening of the coal to eliminate fractions with particles smaller than 1 mm in size made it possible to eliminate the negative effect of the dust on the efficiency of the Kh-34B vessels (vessels Nos. 1-3).

These experiments demonstrated that to improve the parameters of the SVTI in Kh-34B cryogenic vessels it is necessary to find methods of reducing the transfer of heat by means of radiation and through the solid. With prolonged operation of the vessels, the transfer of heat through the gas also becomes significant, as does the formation of a cryogenic precipitate in layers of temperature 80-180 K. In order to eliminate these, we have carried out special experiments involving a vessel in which synthetic USNT-10 paper was used as an intermediate SVTI layer to which a carbon adsorbent had been added. The experiments demonstrated that in the course of a year of operation no increase in vaporization for the vessel was observed, which indicates exclusion of the cryogenic precipitate and any additional transfer of heat through the gas. In order to achieve a maximum increase in the serviceable life of the Kh-34B vessels through the utilization of SVTI-7 frosted glass, we must also eliminate the yellowing of the glass during heat treatment and pasting to the SVTI screens with the PVA emulsion during the vacuum heat treatment. Special experiments showed that this phenomenon can be substantially weakened by prolonged preliminary vacuum heat treatment of the frosted glass.

It is also necessary to eliminate the formation of dust in the adsorption pump of the vessel by housing it in a special filtration material, through preliminary screening of the dust, and also through use of an adsorbent having a small coefficient of radiation absorption.

NOTATION

T, temperature; λ_{eff}, λ_{rad}, λ_{con}, λ_g are the effective coefficients of SVTI thermal conductivity and the radiant, conductive, and gas components of heat transfer, respectively; q, density of the heat flow; ΔT, temperature difference; δ, SVTI thickness; $\Delta\delta$, thickness of the elementary SVTI layer; ε, emissivity of the SVTI screens; ε_{cry}, emissivity in the presence of a cryogenic precipitate; N, number of layers in the packet; σ, Stefan–Boltzmann constant; τ, duration of time after the vessel has been filled with liquid nitrogen; $\Delta\lambda_{rad}$, addition of the radiant component to the SVTI on intensified contact with the screens of the absorbing intermediate layers.

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THE TRANSFER OF HEAT AND MASS IN CAPILLARY-POROUS MATERIALS IN THE HYGROSCOPIC STATE ON DRYING BY MEANS OF REDUCTION IN PRESSURE

R. G. Safin, V. A. Lashkov, and L. G. Golubev

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A mathematical model has been developed for the process of removing multicomponent moisture from disperse capillary-porous materials during the second drying period.

Selection of an optimum drying regime and development of efficient equipment designs to ensure required technological properties for materials to be dried are based on the solution of differential heat- and mass-transfer equations.

A description of the process for removing multicomponent moisture from capillary-porous materials by reduction of pressure in the second period of drying by a system of differential equations [1] involves certain difficulties resulting from the interaction of the components of the mixture in the course of their diffusion, the penetration to greater depths of the vaporization zone, and by such variable criteria of vaporization as the particle coordinate and time [2].

To derive analytical relationships describing the kinetic process, we made use of the Lykov solution [2] which corresponds to a simplified drying mechanism in the form of immersing the vaporization surface under the assumption that the i-th component of the mixture is transferred according to the principle of independent diffusion [3]. During the process of drying by means of pressure reduction, the inert gas is removed from the chamber at the very beginning of the process; consequently, we assume that the drying will subsequently occur in the vapor medium of the moisture that has been removed.

The distribution of the moisture content and temperature through the cross section of a particle which exhibits the shape of an infinite plate, according to the Lykov solution, is linear in nature in the vaporization zone:

$$U_{1i} = (U_{si} - U_{\xi i})\frac{x-R}{\xi} + U_{si},$$
$$T_{1m} = (T_{ms} - T_{m\xi})\frac{x-R}{\xi} + T_{ms}, \quad (1)$$

while in the moisture zone it is parabolic:

$$U_{2i} = U_{ci} - \left(\frac{x}{R-\xi}\right)^2 (U_{ci} - U_{\xi i}),$$
$$T_{2m} = T_{mc} - \left(\frac{x}{R-\xi}\right)^2 (T_{mc} - T_{m\xi}). \quad (2)$$

The boundary conditions for the vaporization zone ξ can be formulated in the following manner:

$$T_{ms} = T, \quad (3)$$

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