the parameter $(\dot{\tilde{Q}}/\dot{V}_V)_2$ during pumping direct comparison of the experimental results with and without the copper mass is impossible. Thus, we have performed an experimental study of the process of cooling by cryoagent vapor pumping. The results confirm the validity of the calculation method proposed previously [7]. An analytical expression has been obtained for determination of the minimum attainable temperature as a function of the parameters characterizing the cooling process.

NOTATION

C, specific heat; i, specific enthalpy; m, mass; $\dot{m}$, mass pumping rate; p, pressure; $\dot{Q}$, heat influx; T, temperature; V, volume; $\dot{V}$, volume pumping rate; u, specific internal energy; $\Gamma = V_m/V_0$, geometric parameter; $\theta = (m_0 - m)/m_0$, relative mass fraction of pumped liquid; $\phi = (V_0 - V)/V_0$, relative volume fraction of pumped liquid; ρ, density. Subscripts: 1, parameters corresponding to first characteristic value of ratio $(\dot{Q}/\dot{V}_V)$; 2, parameters corresponding to second characteristic value of ratio $(\dot{Q}/\dot{V}_V)$; 0, initial values; ~, dimensionless parameters; p, parameters at pump; v, vapor; m, value on submerged mass surface; tp, triple point; s, saturation.

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FACTORS AFFECTING THE RELIABILITY OF PRECISION MEASUREMENT OF LIQUID HELIUM TEMPERATURE IN A DYNAMIC REGULATION AND STABILIZATION MODE

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A study has been made of anomalies detected during precision measurements of liquid helium temperature, using secondary thermometers in a dynamic mode. An explanation is suggested for the physical nature of these anomalies.

The ever growing interest in precision measurement and stabilization of the temperature of experimental equipment in liquid helium has made it essential to study the heat exchange process and the dynamics of the temperature of liquid helium under variable conditions. The studies were carried out in a KG-100 cryostat [1] as applied to the problem of ensuring that the temperature of an experimental device immersed in the liquid helium remains stable (with an accuracy of the order of 10^{-3} K) for a long time. The heat release of the device during active operation was of the order of 0.2 W (constant thermal background) with a fluctuation

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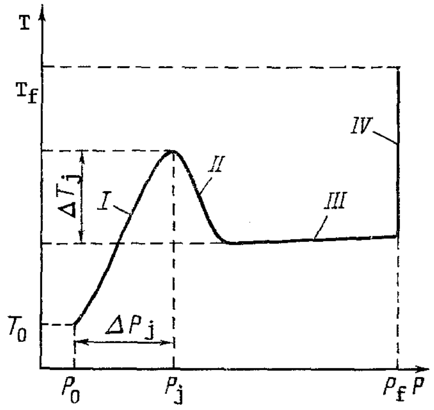

Fig. 1. Graph of T(P) during transient process.

of about 0.02 W in the perturbing thermal pulses, having an irregular on-off time as well as irregular leading and trailing edges. The temperature of the experimental device was assumed to be equal to the stabilized temperature of the liquid helium washing over it.

It is known [2, 3] that boiling can occur in helium at a copper surface even at a thermal load of 15-20 W/m^2 and a temperature gradient of the order of 10^{-1}-10^{-2} K. The problem of how well the thermometer readings correspond to the real temperature of the liquid under dynamic conditions has been studied many times, e.g., in [4-6].

The experiments were conducted with the aid of encased and caseless thermal converters [7] with electrical resistance $R = (3\text{-}8.0)\cdot10^4$ Ω and $dR/dT = (3\text{-}5)\cdot10^4$ Ω/K near 4.2 K. Semiconducting thermal converters have aroused interest because they have a high, easily varied sensitivity in the temperature range studied. Encased thermal converters perform more reliably [7]. In order to reach the necessary temperature and go to a new temperature as well as to operate in a pressure (temperature) stabilization mode an appropriate pressure is produced in the cryostat by means of the natural evaporation of liquid helium. A study of the dynamics of the helium temperature under these conditions revealed a number of anomalies, which were reported in brief in [8].

Figure 1 shows a typical curve of a transient process, recorded in P vs. T coordinates on an N306 recorder at a measuring current of $1\cdot10^{-6}$ A, using an encased thermal converter (in a nickel tube, diameter $2\cdot10^{-3}$ m and length 10^{-2} m). Before the experiment began the liquid was held for a long time (of the order of 10 h) in a relatively quiescent hydrodynamic state and its temperature T_0 corresponded to the equilibrium pressure P_0. On segment I the shape of the curve corresponded roughly to the function T(P) for liquid helium. When a certain value $P = P_0 + \Delta P_j$ (with a prolonged smooth rise in pressure) the temperature readings of the thermometer changed abruptly (decreaed by ΔT_j) on segment II, after which the temperature again began to rise on segment III, but the slope of the curve was now appreciably smaller than in the first segment. When the temperature was determined with such a thermal converter, placed directly above the surface of the liquid no anomalies were observed in the shape of the T(P) curve and the curves coincided on segment I. Then, at a constant pressure P_f, which was stabilized with a manostat, on segment IV the temperature rose to the value T_j, which corresponded to P_j in the equilibrium state, and the system went over into a steady state. If the system is not taken into a stabilization mode, i.e., if the process is continued along segment III as long as possible, a second jump on it is not observed. The typical value of ΔP_j was $1.6\cdot10^3$ Pa and ΔT_j varied from 10^{-2} to 10^{-3} K. A change in the conditions of the experiment affected the value of ΔP_j, which was reached after a jump in temperature, and also affected the magnitude and character of this jump. If the liquid was in a perturbed hydrodynamic state before the experiment, a jump in the temperature usually did not occur.

Figure 2 shows a number of curves, which were obtained under different experimental conditions. When the curves are plotted in T(τ) curves, additional information can be obtained, i.e., the time τ* taken for the process to develop can be determined and the anomalies that appear in the shape of the T(τ) curve when an abrupt pressure drop occurs and in the stabilization mode can be recorded. The corresponding curves 1 and 2 were obtained by

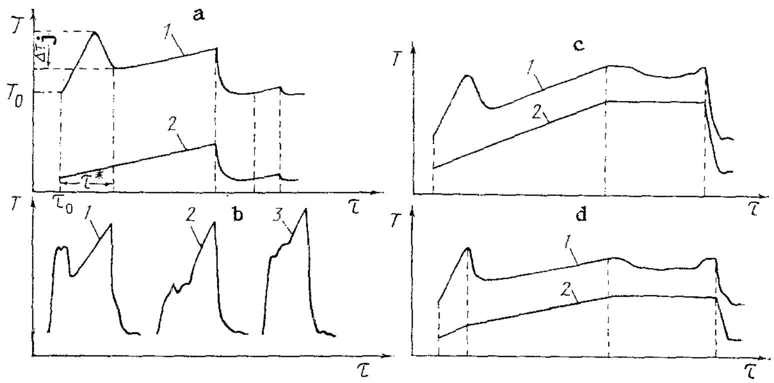

Fig. 2. Graph of T(τ) in a dynamic mode of pressure buildup and release (a, b, c) and with a subsequent transition to a temperature stabilization mode (d): a) parallel recording of the process by means of an encased thermal converter (curve 1) and an caseless converter (curve 2) at a current of 1 μA; b). Successive recordings of the process with an encased thermal converter at a current of 7 μa (1), 9 μA (2), and 10 μA (3).

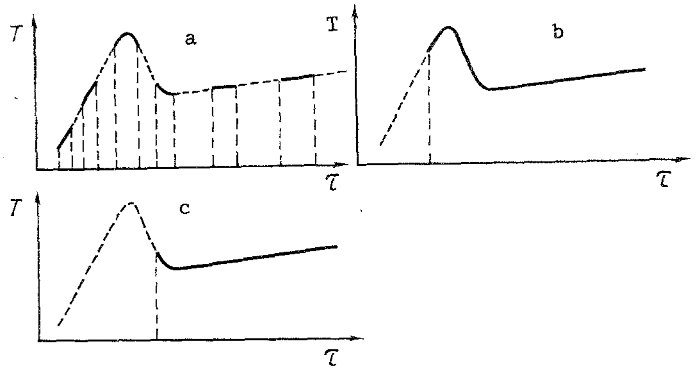

Fig. 3. Recording of the process, using an encased thermal converter: a) with the measuring current switched on periodically; b) with the current switched on an instant before the jump in T; c) with the current switched on during the jump in T.

means of parallel recording of the signals from an encased thermal converter and from a caseless converter. In actual fact curves 1 and 2 begin at one point, but for convenience of imaging they have been separated in regard to T. With the first pressure buildup the shape of the T(τ) curve (Fig. 2a) of the encased thermal converter exhibits a distinct characteristic anomaly in a time τ^* while the T(τ) curve obtained with the caseless thermal converter ascends smoothly. The characteristic development time of the process is $\tau^* \approx 2$ min. After a jump in temperature in the encased thermal converter, both curves run in parallel, and after the pressure release as well. When another pressure buildup follows immediately the T(τ) curves of both thermal converters run in parallel, without any anomalies. An increase in the measuring current in the thermal converter (Fig. 2b) substantially changed the nature of the anomalies in the development of the process, until the temperature jump effect, which occurs at a current characteristic of the given type and size of thermal converter and depends strongly on the experimental conditions, disappears altogether. If heat is released in the experimental device or by some other heater in the liquid helium and the thermal converter is in the zone of the perturbing action of that heat, the effect cannot occur at any measuring current.

Figure 2c represents a recording of the process under a pressure buildup to $\Delta P > \Delta P_j$ and Fig. 2d, to $\Delta P < \Delta P_j$ with a subsequent transition to a pressure stabilization mode. In the initial stage the curves of Figs. 2c and d are similar to the previous curves. Then, with the system not being perturbed by any agencies under the subsequent stabilization mode, the T(τ) curve obtained with an encased thermal converter exhibits new temperature fluctua-

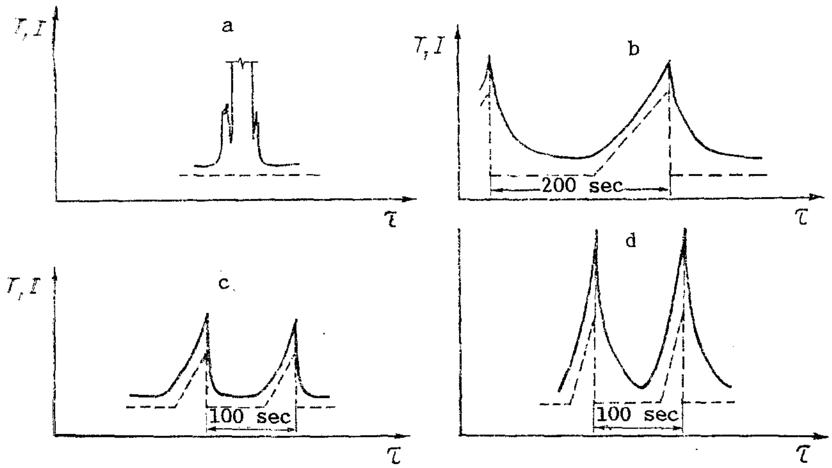

Fig. 4. $T(\tau)$ of a semiconductor thermal converter powered by a generator with current pulses I (dashed line) of various shapes and lengths: a) τ = 200 sec, I_{max} = 1.2 mA, ΔT = 2.5 K; b) I_{max} = 15 μA, $\Delta T = 1.3 \cdot 10^{-2}$ K, c) I_{max} = 19.2 μA, $\Delta T = 1.6 \cdot 10^{-2}$ K; d) I_{max} = 19 μA, $\Delta T = 2.4 \cdot 10^{-2}$ K.

tions, i.e., the temperature decreases by $\Delta T \approx 2 \cdot 10^{-3}$ K and then returns to the previous level. At the same time the caseless thermal converter did not record any fluctuations. Such fluctuations were not repeated after further holding for an arbitrarily long time. From our large series of experiments we can conclude that the times to the onset of this fluctuation (10-100 min) and its duration (2-10 min) differ markedly and depend strongly on the conditions of the experiment it is noteworthy that these fluctuations appeared in the encased thermal converter only if prior to this it had reflected the behavior of the temperature in the initial stage of pressure buildup, regardless of the ΔP at which the transition to the stabilization mode occurs. In the case of parallel recording the caseless thermal converter did not induce any anomalies in the $T(\tau)$ curve during a pressure buildup, while during pressure release, like the encased converter it recorded $T(\tau)$ fluctuations in the initial stage. Later, in the stabilization mode, it again did not record any additional temperature fluctuations, although they were clearly visible in the encased thermal converter.

An anomaly on the $T(\tau)$ curve appeared in encased thermal converters with a narrow saw cut in their casing and also appeared when a caseless thermal converter was wrapped in foil.

We must point out the interrelationship between the depth at which the thermal converter was located in the liquid helium and the measuring current in it and their effect on the shape of the $T(\tau)$ curve.

Thus, an encased thermal converter at a depth of no more than 0.3 m at a current of $1 \cdot 10^{-6}$ A displayed the $T(\tau)$ anomalies in a stable manner while the same converter, placed at a depth of the order of 0.5 m, did not induce any anomalies at the same current. When the measuring current in this converter was increased, however, the effect did appear.

At a greater depth, therefore, all the characteristic anomalies also appear, but only at high measuring currents. Moreover, at the same current an encased thermal converter at the surface reflected anomalies as in Fig. 2b while at some depth the process indicated in Fig. 2a was induced.

The curves shown in Fig. 3 indicate that, regardless of when the measuring current ($1 \cdot 10^{-6}$ A) was switched on, the encased thermal converter clearly reproduced the corresponding part of the developing process in segment I by means of the $T(\tau)$ curve.

A number of studies on heat exchange in He I, e.g., [2, 3], have shown that the history of the thermal load q in the convective heat transfer mode at a given q and underheating in He I has a considerable effect on the heat transfer coefficient α and the value of ΔT. In our case preheating of the thermal converter with a current substantially (10 times) larger than the measuring current did not have any appreciable effect on the nature of the recorded curve.

As already mentioned, the measuring current had a major effect on the shape of the $T(\tau)$ curve of an encased thermal converter. At the same time, we know that in systems with prolonged precise temperature stabilization an alternating current or current pulses several times (3-5 times) the recommended value were applied to the thermal converter in order to increase its signal. Figure 4 shows the results of studies of the $T(\tau)$ of a semiconductor thermal converter powered from a generator with current pulses of various shapes and lengths. The temperature of the liquid and the pressure in the cryostat were stabilized with a manostat. In each case the minimum current was $(0.2\text{-}0.5)\cdot 10^{-6}$ A. Analysis of the experimental results indicates that the higher the final value of the current in a pulse as well as the pulse rise time and fall time, the more the shape of $T(\tau)$ differs from that of the current $I(\tau)$ that induced it. This effect is more distinct in an encased thermal converter. Increasing superheating is noticeable even at a current of $1\cdot 10^{-6}$. Thus, in dynamic measurements at relatively high currents $(3\text{-}20)\cdot 10^{-6}$ A the recorded value of $T(\tau)$ is always higher than the true equilibrium temperature T_* of the liquid by the difference between the nonequilibrium temperatures at the solid—He I interface and is not constant over the cycle:

$$T(\tau) = T_* + \Delta T(\tau). \tag{1}$$

The curve in Fig. 4a was obtained during the increasing heat release in the thermal converter until nucleate boiling begins on its surface. Abrupt fluctuations of the temperature of the thermal converter are observed at the transition from convective heat transfer to nucleate boiling with an increase in the heat load and vice versa with a decrease in the heat load. The hysteresis is very pronounced in this case.

Thus, we have obtained a number of qualitative results which enable us to reveal anomalies in the readings of encased thermal converters during variations of the liquid-helium temperature in a dynamic mode of pressure buildup and stabilization.

For the correct interpretation and reproduction of the true temperature of the liquid for measurement and stabilization it is important to understand what such a series of anomalies in the shape of the $T(\tau)$ curve reflects: processes occurring in the thermal converter itself, or at the solid—liquid interface. Let us consider each of these factors separately.

Because of its physical nature the $R(T)$ function of semiconductor thermal converters does not have such anomalies; otherwise, regardless of the design, they would have manifested themselves at a fixed temperature characteristic of the given material and would not vary with the conditions of the experiment.

Processes occurring in the liquid will be considered from the standpoint of their possible effect on the shape of the $T(\tau)$ curve. The function $T(P)$ for liquid helium equilibrium with the vapor was studied in detail. There are no grounds for assuming that as the vapor pressure increases smoothly or goes into a stabilization mode the temperature of the liquid can change with some irregular anomalies. We must assess an assumption of this kind. Up to the onset of the process in the liquid, in a state of equilibrium with the vapor, the temperature is stratified over the height and this stratification in accordance with the hydrostatic pressure of the column of liquid in the given section. The procedure for raising the temperature by means of a pressure buildup is analogous to the processes that occur when the cryogenic liquid is stored in closed vessels without drainage. From work on drainless storage, e.g., [9], we know that at first in a time τ_f an intensive circulatory process is initiated and stabilized and as a result warmer helium rises. The anomaly revealed in the shape of the $T(\tau)$ curve, however, cannot be a result of convection since the characteristic time τ^* is substantially shorter than τ_f. Moreover, this anomaly is also observed stably when the thermal converter is placed in a styrofoam cup, completely immersed in the liquid helium. The assumption that the pressure in the vessel jumps when the venting of the evaporated helium is cut off instantaneously, which could have been the cause of the temperature rise preceding the pressure jump, has not been confirmed experimentally.

Our analysis unambiguously indicates that the anomaly in the $T(\tau)$ curve in a time τ^* is determined by processes occurring at the surface of the thermal converter, i.e., at the solid—liquid interface. Our previously expressed assumption [8] was that the temperature jump recorded by encased thermal converters is a consequence of the collapse of bubbles on its surface under the effect of the rising pressure. This assumption, however, is evidently oversimplified. A concept of the following kind is more realistic. During a period of thermodynamic equilibrium, when T_1 corresponds to the saturation vapor pressure, the fluctuations cause gas bubbles present within the liquid to coat a considerable part of the surface of the thermal converter. It is in order to assume that the thermometer—He I system is in a state of dynamic equilibrium, i.e., gas bubbles washed off the surface of the thermal converter by hydrodynamic perturbation of the liquid are replaced by new bubbles. In this case a difference ΔT is established between the actual temperature T_1 and the value recorded by the thermal converter. From the standpoint of the physics of the heat transfer semiconductor thermal converters are small heaters operating in a mode with a small thermal load under transient conditions.

A number of recent studies [10] indicate that the temperature difference $\Delta T(\tau)$ at the solid—He I interface is determined by two components,

$$\Delta T(\tau) = \Delta T_{\ell}(\tau) + \Delta T_f, \quad (2)$$

where $\Delta T_l(\tau)$ depends on the heat exchange between the thermal converter and the liquid and ΔT_f is the limiting Kapitza resistance. As follows from the aforementioned studies, the strongest effect on the thermal converter readings [including the value of $\Delta T_l(\tau)$], besides that of the thermal energy, is the effect of the magnitude and nature of the thermal load on the converter (as a result of the passage of the measuring current), the thermophysical properties of the material of the heat-transfer surface, the state and nature of its treatment, its spatial orientation, as well as the thermal and hydrodynamic state of the liquid in the zone where the thermal converter is located. The list of factors affecting the heat exchange between the thermal converter and the liquid and determining $\Delta T_l(\tau)$ should include a layer of gas bubbles which worsens the heat exchange. This situation is characteristic of only convective heat exchange between a thermal converter and liquid in equilibrium with the saturated vapor. Then in the initial stage of a smooth pressure rise with the drainage closed the situation in the liquid at the surface of the thermal converter also changes. The liquid goes into an underheated state and the degree of underheating increases with the pressure. In parallel with this the pressure in the gas bubbles at the surface is increased as a result of compression by the growing pressure of the vapor above the liquid; the temperature T_g of the gas in these bubbles differs from T_s, which corresponds to P at a given moment, even with allowance for some heat influx from the thermal converter, i.e., $T_1 < T_g < T_s$. Conditions conducive to spontaneous condensation arise in the gas bubbles as a result. The main part of the heat of condensation is absorbed by the thermal convector, which is thus superheated further relative to T_1. When the condensation is completed the flow of heat into the thermal converter decreases rapidly and is cooled to the current value T_1 with allowance for the new $\Delta T(\tau)$, i.e., the temperature of the thermal converter jumps by ΔT_f (see Fig. 1). The effect of the experimental conditions on the magnitude and nature of the anomalies detected becomes understandable in this representation of the mechanism of the process. The fluctuations of the thermal converter temperature at a high measuring current, which occur in the final stage of the process (Fig. 2b), are due to the fact that the influx of heat into the gas bubbles from the thermal converter and the condensation take place in jumps. After the next fraction of bubbles condense a minijump occurs and as a result the thermal converter temperature approaches T_s, i.e., the thermal converter and the gas in the bubbles on it are cooled via heat exchange with the surrounding liquid. Conditions for condensation are then again formed in the bubbles. The number and magnitude of the minijumps of the temperature depend on the combination of the actual conditions of the experiment.

A demonstration experiment, in which the system with a low measuring current in the thermal converter was taken into a pressure stabilization mode, was carried out until ΔP_j was reached (Fig. 2d). As soon as the pressure buildup stopped, the condensation rate of the gas in the bubbles decreased and the thermal converter smoothly cooled down to the current value of T_1 with allowance for $\Delta T(\tau)$.

If the thermal converter was placed in the hydrodynamic perturbation zone, whatever the origin of the perturbation, the gas bubbles were "washed off" or did not adhere to the thermal converter surface at all. In any case, the number of gas bubbles was small and they had not appreciable effect on the processes occurring on the thermal converter surface and, consequently, no anomalies were observed in the $T(\tau)$ curve.

We should consider in particular the circumstance that a caseless germanium thermal converter does not record any anomalies in the $T(\tau)$ curve under any experimental conditions. Even though numerous papers have been done on heat exchange in helium, only some of them [11] have indicated the existence of anomalies in the heat exchange of small heaters with the surrounding liquid, which should be characteristic of convective heat transfer in particular. The caseless thermal converter is cube-shaped (measuring $1 \cdot 10^{-3}$ on a side) and all six of its heat-transferring surfaces are oriented in different ways in space, thus inevitably affecting the nature of the heat transfer with the liquid in this situation it seems quite correct to assume that the caseless thermal converter does not record anomalies in the $T(\tau)$ curve because of the effect of the small dimensions necessary for similar processes to form on the surface and because efficient thermal contact cannot be made with the liquid. It is pertinent to note here that this refers not simply to the fact that the total surface area is small and but also that it consists of separate microscopic areas, oriented in different ways in space. The additional effect of this circumstance has been confirmed experimentally with a custom-built thermometer, in which the semiconductor crystal of the thermal converter was soldered to a sapphire substrate (a square wafer with thickness $1 \cdot 10^{-3}$ m). The total area of the surface was kept roughly equal to the surface of the encased thermal converter. Despite this, in all the experiments the new thermal converter, like the caseless thermal converter, did not record any anomalies in the $T(\tau)$ curve.

In accordance with the discussion above, we can say that when heat exchange occurs between solid with complex shapes (e.g., encased and caseless thermal converters) with the liquid the conventional concept of specific thermal load is meaningless. It is necessary, therefore, to analyze the conditions of heat exchange with the liquid separately for each small area with allowance for the effect and nature of its thermal contact with the heat source, the storage capability, the state of the surface, and its spatial orientation. This comment also holds for the relatively large experimental device (vertical cylinder of diameter 0.1 m and height 0.15 m with flat lids) that we studied. Heat is drained primarily from separate small local areas, with a good thermal contact with the internal heat source.

The results of our study also show that extreme caution must be taken in assessing the metrological reliability of the interpretation of the true liquid temperature, measured under conditions of dynamic regulation and stabilization of this temperature. In the general case the current value of the temperature $T(\tau)$, recorded by the thermal converter, is a composite function of the variables of the true value of $T_1(\tau)$ and the gradient $\Delta T(\tau)$ at the solid–liquid (gas) interface.

The proposed mechanism of the initiation and development of the process in the initial stage of pressure buildup makes it possible to find a satisfactory explanation for all the anomalies in the $T(\tau)$ curve and also provides a key to understanding the mechanism of the subsequent fluctuation of $T(\tau)$, which occurs during pressure and temperature stabilization.

NOTATION

T_0 and $T(P)$, temperature (in K); ΔT_j, temperature jump (in K); T_f, final temperature (in K); $T(\tau)$, equilibrium temperature of the thermometer (in K); $T_1(\tau)$, equilibrium temperature of the liquid (in K); T_0, temperature of the gas in the bubbles (in K); T_s, temperature of the saturated vapor above the liquid helium (in K); $\Delta T(\tau)$, nonequilibrium temperature difference at the solid–He I interface, which is determined by the heat exchange with the liquid; ΔT_f, temperature jump at the solid–liquid interface; P_0 and P, pressures (in Pa); ΔP_j, increase in pressure up to the jump (in Pa); P_f, final pressure (in Pa); τ, time (in sec); τ_f, initiation time of the circulation process (in sec); q, thermal flux density (W/m^2); R, resistance of the thermal converter (Ω); dR/dT, sensitivity of the thermometer (in Ω/K); and α, heat transfer coefficient.

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