BOILING UP OF HELIUM I, HELIUM II, AND NITROGEN DURING TRANSIENT HEAT RELEASE

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The boil-up times of He I, He II, and liquid nitrogen are measured and their connection with the temperature of homogeneous nucleation is established.

The practical utilization of superconducting devices and instruments gives urgency to the investigation of the thermophysical properties of He I and He II. Local losses of superconductivity developing under emergency conditions during the operation of these devices cause highly transient heat release and corresponding processes of heat exchange with the coolant. The importance of experiments on nonsteady heat exchange in He I and He II is increased by the notably specific nature of heat exchange in them.

In [1, 2] experiments are described where rapid heatup of wires in the liquid was used to measure the temperature of homogeneous nucleation. The temperature dependence of the resistance of wires that was used, however, becomes weak at helium temperatures. In other papers [3, 4], information on processes in He I is obtained from the volt—ampere characteristic curves of carbon and platinum films. In [5] the method of magnetoresistance thermometry during heating of a bismuth crystal was used to measure superheating in He I.

An experiment to study the boilup of He I, He II, and nitrogen during the heating of a thin Nichrome film on a quartz backing is described below. Knowing the heat-release density q and the time t_A from the start of heating to the appearance of a signal on the piezosensor (the time of appearance of the signal is identified with the time of onset of nucleation, or of boilup), the temperature of the heater can be derived from a calculation by the equation of transient heat conduction. It turns out to be close to the temperature of limiting superheating, obtained from the theory of homogeneous nucleation.

The instrumental part of the installation is made up (see Fig. 1) of a rectangular-pulse generator (G5-35) 1, an amplifier 2, and an oscillograph (S8-13) 3. The experimental cell consists of a bracket (not shown), to which the backing 5 of quartz glass (a disk 50 mm in diameter and 5 mm thick) is fastened, on one side of which the nichrome film heater 4 (a 3 × 3 cm square) and contact areas of silver are deposited, while a piezosensor 6 (a plate of TsTS-19 lead zirconate titanate 1 mm thick and 5 × 5 mm in size) is soldered to the other size with indium. The cell is placed inside a helium cryostat, the liquid temperature in which is determined from the pressure of saturated vapor and is varied by evacuating it. The experiments were carried out on the saturation line. The orientation of the heater, "face" down at an angle of $\pi/6$ rad to the vertical or "face" up, horizontally, did not affect the measurement of t_A. The passage of a rectangular current pulse through the nichrome film causes heat release with a constant density q, since its resistance (100 Ω) varied by no more than 4% in the temperature range of 1.5-300°K. The resonance frequency of the piezosensor is ∿5 MHz, and together with the high speed of sound in the quartz glass, this results in a small error in measuring t_A (∿1 μsec), connected with passage of the signal through the backing and with frequency distortions in the sensor. The frost condensing on the surface of the heater was found to have a strong influence on t_A.

The time taken as the start of boilup is marked by arrows on characteristic oscillograms of the piezosensor signal in He II in Fig. 2.

The measured times t_A as a function of q are presented in Fig. 3.

The temperature of a thin heater at the backing—liquid boundary between two semiinfinite media, for a constant density of heat release and temperature-independent thermophysical properties of these media, is given by the following solution of the heat-conduction equation

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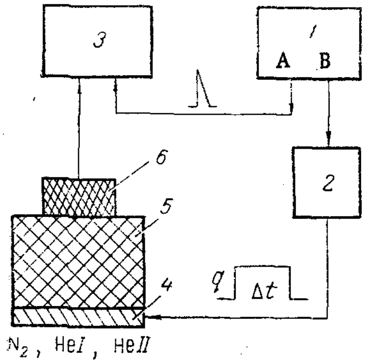

Fig. 1. Diagram of the experimental setup.

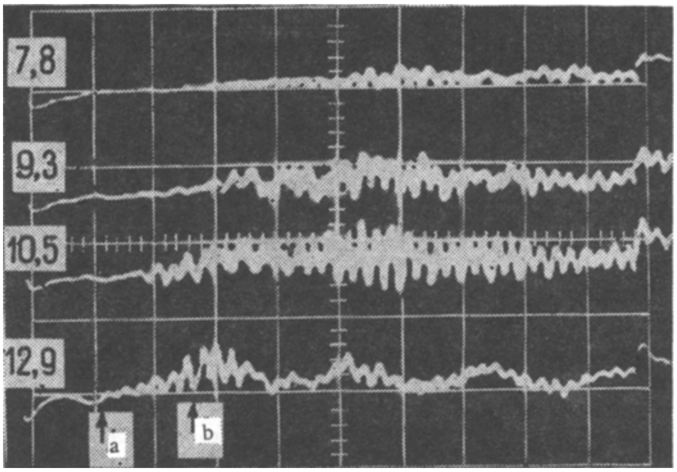

Fig. 2. Oscillograms of the acoustic signal in the boilup of He II. Numbers denote the heat-flux density, 10^4 W/m^2; sweep 1 msec/division; T = 1.884°K.

[6]:

$$T_h = T_\infty + 2q\sqrt{t}\,[\sqrt{\pi}\,(\sqrt{(\lambda c\rho)_l} + \sqrt{(\lambda c\rho)_b})]^{-1}, \tag{1}$$

where T_∞ is the liquid temperature before heating; t, heating time; the indices b and l refer to the backing and the liquid; the values of λ, c, and ρ are taken from [7]. The layer of liquid heated above the saturation temperature to a depth $\delta \sim \sqrt{at}$ boils up when T_h becomes equal to T_*. The value of T_{*e} obtained from measurements of t_A can be compared with the corresponding temperature T_{*p} obtained from the theory of homogeneous nucleation, in which the specific nucleation frequency was calculated from the formula [1]

$$J_1 = N_1 B \exp(-W_{cr}/kT), \tag{2}$$

where ln $(N_1B) = 88$; W_{cr} is the work of formation of a critical nucleus; k is the Boltzmann constant; T is the temperature. Upon heating to the temperature T_*, the probability of formation of a critical nucleus is $J = 1$, and then for our case we can obtain an equation for J_1,

$$J = J_1 tS\delta = 1, \tag{3}$$

where S is the heater area while $t = t_A$, and we can find T_{*c} from (2).

In Table 1 we present values of T_{*e}, obtained from (1), and T_{*c} from a calculation based on (2) and (3). The good agreement of these values indicates the correctness of the initial premises.

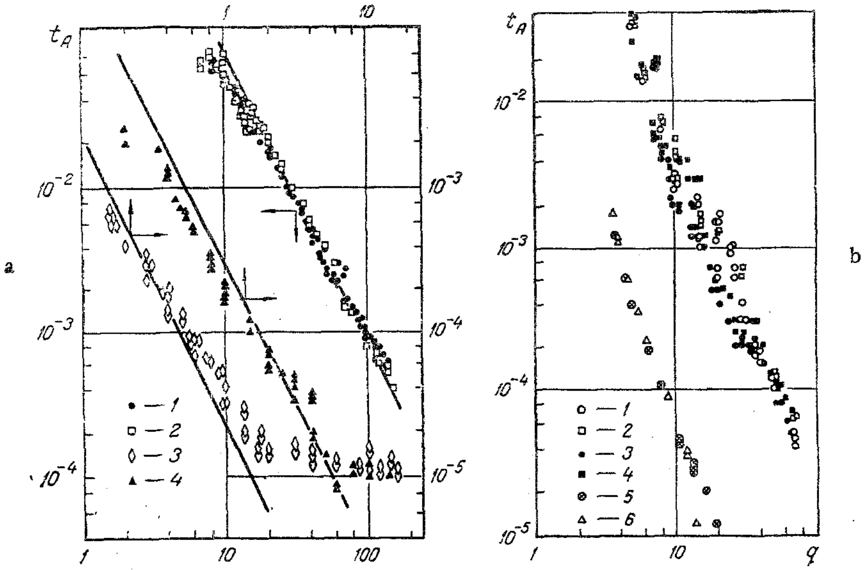

Fig. 3. Boilup times t_A, sec, of nitrogen, He I, and He II as functions of the heat-flux density q, 10^4 W/m^2, on the heater: a) 1, 2) N_2, T = 77.4°K; 3) He I, T = 4.22°K; 4) He I T = 2.3°K; 3, 4) backing of quartz glass; 2) backing of Kron-8 glass; solid lines) calculation from Eqs. (1)-(3); b) measurements in He II: 1, 2) T = 1.794°K; 3, 4) T = 1.884°K; 1, 3) measurement of t_A from start of the signal (Fig. 2, arrow a); 2, 4) from maximum of the signal (Fig. 2, arrow b); 1-4) f = 1/40 Hz; 5, 6) T = 2.111°K; 5) f = 1 Hz; 6) f = 1/60 Hz.

TABLE 1. Temperatures of Limiting Superheating

Substance	T_{*e}, K	T_{*c}, K
Nitrogen, 77.4°K	108,5±0,7	111
He I, 4.22°K	4,68±0,06	4,6
He I, 2.3°K	4,40±0,17	4,3

The values of t_A that we obtained for nitrogen agree well with measurement data with the corresponding q presented in [3, 4, 8].

The functions $t_A(q)$ that we measured for He I are only in qualitative agreement with the results presented in [9, 10], while good agreement is observed with the calculation presented in [3]. The data of our measurements for 4.22°K, if they are depicted on the appropriate lines in Fig. 3 of [3], lie at the start of the "metastable nucleation period" region with good accuracy. Thus, the boilup, recorded from the pressure jump, does not lead instantaneously to an increase in the temperature of the film heater, which occurs after a certain time dependent on q: For $q = 1 \cdot 10^4$ W/m^2, the time of a sharp temperature rise is 3 msec, while the time of the pressure jump or boilup is 30-40 μsec [3].

Heat-exchange processes in superfluid helium are especially complicated. At present there is insufficient information for complete and systematic allowance for such phenomena, inherent to He II, as the Kapitza jump at the heater—helium boundary, waves of second sound formed during pulsed heat releases, and vortex formation in the superfluid component of He II [11], and the He II—He I phase transition occurring in the metastable liquid during the same type of heating [12]. Nevertheless, because of the similarity of the $t_A(q)$ functions, we can assume that processes with classical heat conduction dominate during such pulsed heat releases in He II, and for it we introduce the effective coefficient of heat assimilation κ [$W \cdot {}^\circ K^{-1} \cdot sec^{1/2} \cdot m^{-2}$] (equal to $\sqrt{\lambda c \rho}$ for an ordinary liquid), which equals $(0.24 \pm 0.05) \cdot 10^4$ at 1.884°K and $(0.04 \pm 0.01) \cdot 10^4$ at 2.111°K according to our measurements. The similarity of the $t_A(q)$ functions for He II, on the one hand, and for He I, on the other, serves as confirmation that a layer of metastable helium is formed near the heater. The absence of a dependence of t_A on f gives reason to assume that in the corresponding ranges of q and f at 2.111°K, vortex formation does not affect boilup (nevertheless, it is obvious that in increase in f must influence the function $t_A(q)$ at some time, since larger f are equivalent to steady heat release).

In [13] the times Δt^* of development of boilup in He II were measured, and it was found that $\Delta t^* \sim q^{-4}$. In our measurements one can also note that for $q < 10 \cdot 10^4$ W/m^2 the functions $t_A(q)$ have a considerably larger slope than for $q > 10 \cdot 10^4$ W/m^2; evidently, the function $t \sim q^{-4}$ arises for small q.

The further development of this method of measuring T_* (or κ) entails the enlistment of numerical methods of calculation, in which the temperature dependence of the thermophysical properties of substances must be taken into account.

NOTATION

q, heat-flux density; t_A, time from the start of heating to the appearance of a signal on the piezosensor; t, time; T_h, T_∞, heater and bath temperatures; T_*, temperature of limiting superheating; λ, coefficient of thermal conductivity; c, specific heat; ρ, density; δ, characteristic heating depth; a, coefficient of thermal diffusivity; κ, coefficient of heat assimilation; f, frequency.

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