EXPERIMENTAL INVESTIGATION OF HEAT TRANSFER WHEN THE SURFACE OF THE SUPERCONDUCTING CERAMIC $YBa_2Cu_3O_7$ IS COOLED WITH LIQUID NITROGEN. 1. HEAT EMISSION UNDER THE CONDITIONS OF BUBBLE BOILING

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Heat emission under the conditions of bubble boiling of nitrogen on flat, horizontal, metal—oxide—ceramic heaters was investigated in the pressure range $1.3 \cdot 10^4$-$1.2 \cdot 10^6$ Pa.

The conditions for stabilization of current—nitrogen-cooled high-T_c superconductors are largely determined by the characteristics of heat transfer between the cooled surfaces of the elements and the refrigerant [1-3]. The characteristics of heat emission under the conditions of boiling of liquid nitrogen on high-T_c material have not yet been studied. It can be conjectured that the characteristics of heat transfer under these conditions will be different from those observed in the case of boiling on smooth metallic surfaces because of the porous structure of the ceramic and the low values of the heat-assimilation coefficient of high-T_c materials [4].

To study the boiling of nitrogen on the surface of the metal-oxide superconducting yttrium ceramic $YBa_2Cu_3O_7$, four cylindrical samples were prepared, at the Scientific Production Union "Monokristallreaktiv," from powder by the method of cold pressing. The characteristics of the samples are given in Table 1. The construction of the heater unit, assembled based on one of the samples, is shown in Fig. 1. The exothermic surface 3 was the end of the sample 2, on whose end an electric heating element made of constantan wire 5 was glued. The element is separated from plastic-foam thermal insulation 1 by a plate 6, made of fabric glass laminate, prevents the thermal insulation from burning up. The temperature T of the ceramic was measured with copper—constantan differential thermocouples 4, placed into 0.75 mm in diameter radial drilled holes and inserted into fluoroplastic centering inserts (one thermocouple in each of the samples Nos. 2 and 4, two thermocouples in No. 1 and six thermocouples, which were inserted into the thermal insulation; these thermocouples were used to estimate the loss of heat through the plastic foam in the radial and axial directions (the losses do not exceed 5%). The outer surface of the plastic foam was covered with BF-2 glue. The thermoemf of the thermocouples and the parameters of the heating-element circuit were measured with the help of V7 21 digital voltmeters.

The experiments were conducted in two cryostats (metallic and glass) at pressures p ranging from $1.3 \cdot 10^4$ to $1.2 \cdot 10^6$ Pa. The exothermic surface was horizontal. The heat flux density q was calculated by dividing the power of the heating element by the area of the exo thermic surface. It should be noted that the effective contact area between an open porous structure, which the ceramic sample is, and a liquid refrigerant is greater than the area of a smooth exothermic surface. It is also quite difficult to determine the temperature of the exothermic surface Texo, became heat transfer in the porous structure occurs not only as a result of heat conduction in the framework but also as a result of the evaporation and condensation of the refrigerant. Because of this, Texo was determined by means of extrapolation from the indications of the thermocouples on the heaters Nos. 1 and 3 and the surface temperature of the heaters Nos. 2 and 4, each of which has one thermocouple, was calculated with the help of the heat-conduction equation. The effective thermal conductivity λ_{eff} was estimated experimentally; in the working temperature range it decreases slightly as T increases and depends strongly on the density of the high-T_c material. For example,

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TABLE 1. Characteristics of High-T_c Samples

No. of sample	Diameter	Thickness	Density, 10^3 kg/m^3	Porosity, %	Critical temp., K
	mm				
1	20,2	6,3	4,70	26,2	90,8
2	22,0	3,1	5,30	16,8	90,6
3	30,5	15,4	4,50	29,4	92,8
4	20,0	2,0	4,54	28,7	90,5

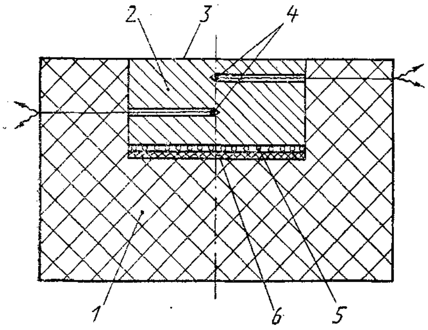

Fig. 1

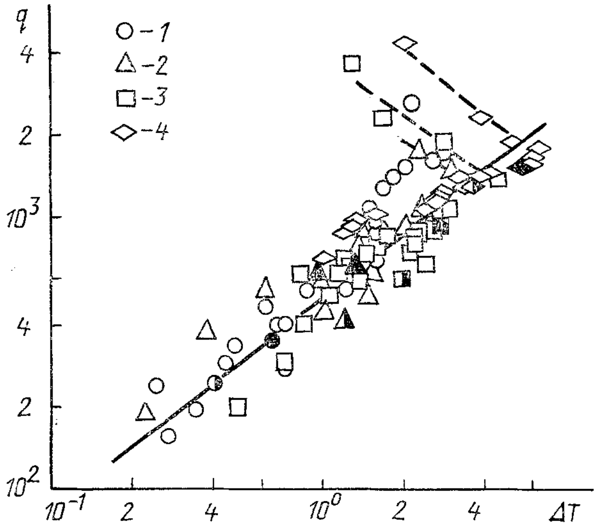

Fig. 2

Fig. 1. Heater unit with sample No. 1. The numbering is explained in the text.

Fig. 2. Dependence $q = q(\Delta T)$ in the region of single-phase convection and boiling of liquid nitrogen on sample No. 3: 1 — $p = 10^5$ Pa; 2 — $5 \cdot 10^4$; 3 — $2.5 \cdot 10^4$; 4 — $1.3 \cdot 10^4$; the solid black symbols correspond to boiling of liquid nitrogen as q increases; the half-black symbols correspond to stoppage of boiling as q decreases; the solid line was computed using the relation $q = 510\ \Delta T^{0.787}$; the dashed lines correspond to transition to developed bubble boiling.

at T = 150 K the thermal conductivity of the samples with density $\rho_h = (4.50, 4.70, 5.30) \cdot 10^3$ kg/m^3 is equal to $\lambda_{eff} = 1.64$, 2.30, and 3.70 W/(m·K); this is in good agreement with the averaged data, obtained by other authors, on the dependence $\lambda_{eff} = \lambda_{eff}(\rho_{exo})$.* This method of determining T_{exo}, combined with the use of centering inserts, which reduce the uncertainty in the position of the working junctions of the thermocouples, made it possible to obtain much more reliable results than in [4].

The boiling of liquid nitrogen on the exothermic surface was investigated for sample No. 3 in a glass cryostat. The power of the heating element was increased in steps from zero and was maintained constant at each step for a long period of time. For low values of q heat was emitted on the surface of the ceramic in the regime of single-phase convection; at certain values of q_0 and ΔT_0 the first vapor bubbles appeared ($\Delta T_0 = T_{exo,o} - T_s$, where T_s is the saturation temperature). When the heat flux density was reduced, bubble detachment stopped at values of q_1 and ΔT_1 lower than the values of which bubbles start to appear. In the course of the experiments the process of boiling was photographed with a Zenit-E camera fitted with a Tair-11 telescopic objective.

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*Yu. A. Kirichenko, K. V. Rusanov, and E. G. Tyurina, "The thermal conductivity of high-T_c superconducting materials (review of experimental data)," Preprint No. 31-89, Physicotechnical Institute of Low Temperatures of the Academy of Sciences of the Ukrainian SSR, Khar'kov (1989).

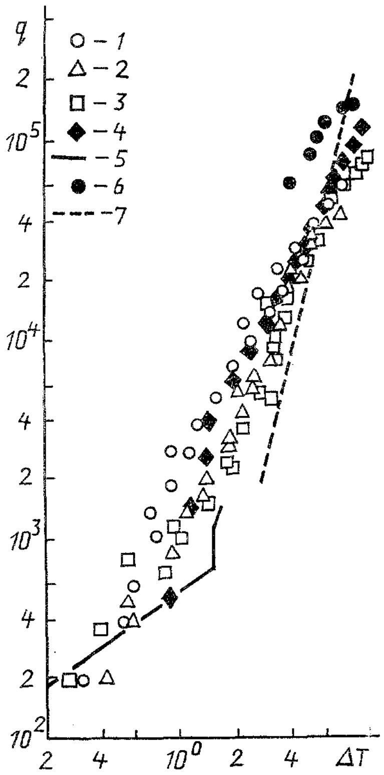

Fig. 3

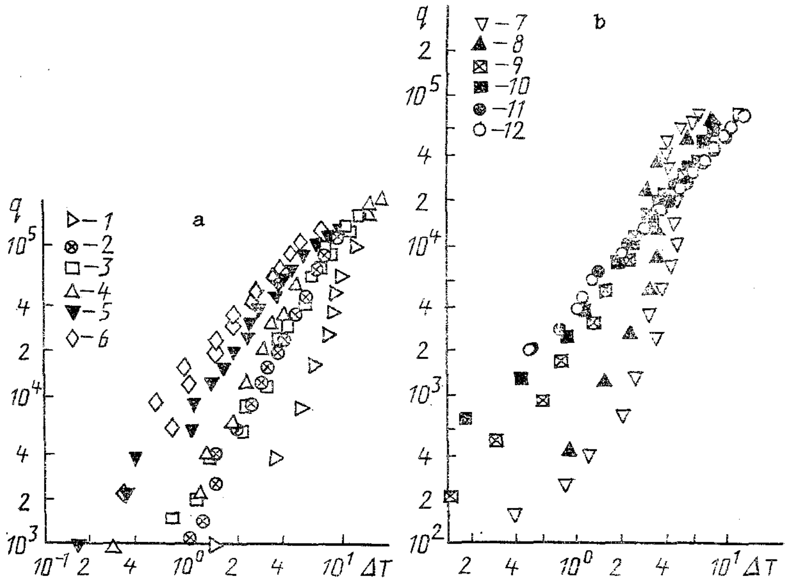

Fig. 4

Fig. 3. Dependence q = q (ΔT) with bubble boiling of nitrogen at atmospheric pressures on different samples: 1-3) results of repeated experiments on sample No. 1; 4) sample No. 2; 5) No. 3; 6) No. 4; 7) calculation using the relation $a = 2.27 \cdot q^{0.761}$ [5] (flat copper heaters).

Fig. 4. Dependence q = q (ΔT) in the regime of bubble boiling of liquid nitrogen under different pressures: a) on sample No. 2: 1 — $p = 5 \cdot 10^4$ Pa, 2 — $1 \cdot 10^5$; 3 — $2 \cdot 10^5$; 4 — 4.10^5; 5 — $7 \cdot 10^5$; 6 — $1 \cdot 10^6$; b — on sample No. 1: 7 — $p = 1.3 \cdot 10^4$ Pa; 8 — $4 \cdot 10^4$; 9 — $2 \cdot 10^5$; 10 — $6 \cdot 10^5$; 11 — $1 \cdot 10^6$; 12 — $1.2 \cdot 10^6$

The results of the investigations of heat emission are presented in Fig. 2. The quantities q_0, q_1, ΔT_1 increase as the pressure increases, like in the case of heat emission from smooth metallic surfaces [5]. The absolute values of the characteristics of boiling and stoppage of boiling on a metal-oxide ceramic fall between the values observed when liquid nitrogen boils on smooth metallic surfaces [5] and on heaters with metallic porous-capillary coatings (CPC) [6, 7]. For example, in [6] boiling on a copper CPC occurred at $\Delta T_0 = 0.4$ K, while in [7] as q decreased the boiling remained for $\Delta T \leq 0.35$ K ($p = 10^5$ Pa and $\Delta T \leq 0.6$ K ($p = 1.96 \times 10^4$ Pa); this is less than in Fig. 2. This result can be explained by the interaction of two factors: the porous structure of the ceramic facilitates boiling of liquid nitrogen compared with the smooth metallic surface, but the low, compared with metals, thermal conductivity of the framework partially compensates this effect.

It is obvious from Fig. 2 that the deviation of the data from the gently sloping part of the dependence q = q(ΔT) (i.e., the transition to bubble boiling as to the heat-transfer regime) occurs for heat loads greater than q_0, and in the case of low pressures this transition is accompanied by a decrease of the temperature head. For this reason, another characteristic of the heat flux density, should be noted. The heat flux density varies from $q_2 \approx 10^3$ W/m^2 at $p = 1.3 \cdot 10^4$ Pa. In the interval (q_0, q_2) the exothermic surface is filled with active centers of evaporation. For $q \geq q_2$ there appears in the base of the porous ceramic sample a zone in which the temperature gradient is much larger than in the rest of the cylinder. The thickness of this zone increases as q increases; here the liquid in the interpore channels is apparently partially or completely "dried up" [8].

The detachment diameters of the vapor bubbles D_d were determined from photographs of the boiling of liquid nitrogen on isolated centers of evaporation, i.e., at $q = q_0$, $\Delta T = \Delta T_0$. For pressures $p = (1.0;\ 0.5;\ 0.25;\ 0.13) \times 10^5$ Pa the values $D_d = 0.42 \pm 0.02;\ 0.62 \pm 0.02;\ 0.91 \pm 0.05;\ 2.57 \pm 0.63$ mm, respectively, were obtained. These values agree satisfactorily with the data on the boiling of liquid nitrogen on a steel thin-walled tube in the same pressure range: at $p = (1.0;\ 0.7;\ 0.45;\ 0.22) \cdot 10^5$ Pa, $D_d = 0.4;\ 0.5;\ 0.6;\ 1.6$ mm (see [5, Table 3.1, series II).

The average diameter of the depressions in the exothermic surface D_c can be estimated from the bubble detachment diameters of the bubbles using the formula for a quasistatic detachment regime [5].

$$D_d = 1{,}74 \sqrt[3]{\frac{\sigma D_c}{g(\rho - \rho_V)}}, \tag{1}$$

where g is the acceleration of gravity, σ is the surface tension, and ρ and ρ_V are the density of the liquid and vapor, respectively. The data obtained at $p = 10^5$ and $5 \cdot 10^4$ Pa can be referred to this regime [5]. Based on the formula (1) and the experimental values of D_d we obtained $D_c = 2 \cdot 10^{-5}$ m. The value of D_c can be estimated independently using the formula

$$D_c = \frac{4B\sigma T_s}{L\rho_V \Delta T_0}, \tag{2}$$

where for cryogenic liquids $B \approx 10$ [5] and L is the heat of vaporization. Substituting into Eq. (2) the experimental values of ΔT_0 gives $\bar{D}_c = 4.3 \cdot 10^{-5}$ m. A visual analysis and photographs of the exothermic surface of sample No. 3 on an Ala-Too microscope setup (IMASh-20-75) with a magnification of 750 showed that the grain sizes of the high-T_c material and the openings of the pores are equal to $(1\text{-}4) \cdot 10^{-5}$ m. Thus indirect estimates of D_c, obtained from the formulas (1) and (2), satisfactorily agree with the real structural characteristics of the ceramic.

Figure 3 shows the data on the dependence $q = q(\Delta T)$ at atmospheric pressure. These data were obtained on heaters Nos. 1-4, including in repeated experiments, performed on different days (sample No. 1). Comparing the obtained results with the data on the boiling of liquid nitrogen on flat copper heaters it can be concluded that the dependence $q = q\ (\Delta T)$ in the case of boiling on samples of $YBa_2Cu_3O_7$ is weaker than on copper. The generalization of the data obtained on heaters Nos. 1 and 2 for heat loads ranging from 10^3 W/m^2 up to 10^5 W/m^2 gives $q = 1.33 \cdot 10^3 \cdot \Delta T^{1.98}$ or $a = 39.2 \cdot q^{0.489}$. The second feature, which can be seen in Fig. 3, of the boiling of liquid nitrogen on the ceramic is that some degradation of heat emission occurs as the thickness of the sample increases but the overall character of the dependence $q = q\ (\Delta T)$ remains unchanged, i.e., the boiling curve shifts to the right. Both these effects are analogous to those observed in the case of boiling of liquid nitrogen on metallic [6, 7, 9] and nonmetallic [10] CPC, and they are apparently of the same nature.

The data on the effect of pressure on heat transfer under conditions of bubble boiling of liquid nitrogen on a ceramic are presented in Fig. 4. As one can see, the character of the pressure dependence of heat emission is strongly affected by the thickness and porosity of the sample. As the pressure increases the curves $q = q(\Delta T)$, obtained on the thin sample No. 2 with low porosity, systematically shift to the left into the region of low temperature heads; the exponent in $q \sim \Delta T^n$ decreases (Fig. 4a). This effect of the pressure on the dependence $q = q\ (\Delta T)$ is characteristic for boiling of liquid nitrogen on smooth metallic surfaces [5]. Superposition of the curves of boiling on a ceramic sample on one another, i.e., pressure independence of the heat-transfer coefficient, is observed only under high thermal loads ($q > 10^5$ W/m^2).

The situation changes substantially in the case of boiling on sample No. 1, whose porosity is relatively high and which is twice as thick as the sample No. 2 (Fig. 4b). Here the region of heat loads where heat emission systematically improves as the pressure increases is significantly narrower than in the case of Fig. 4a and is limited above by the value $q \approx 1.5 \cdot 10^4$ W/m^2. Above this value a unique inversion of the boiling curves is observed, and the dependence $a = a\ (p)$ is inverted. The boiling curves, corresponding to higher pressures, merge (as in the top part of Fig. 4a), and all curves acquire the same slope, close to the linear dependence $q \sim \Delta T$.

It can be conjectured that the results obtained in our experiments are determined by the specific mechanism of heat and mass transfer accompanying boiling in open porous structures. Thus the existence of a linear dependence $q = q(\Delta T)$ is explained in the literature by the formation of a continuous vapor layer at the base of the porous structure [8-10]. It is clear that as the thickness of the porous structure increases (and the resistance to the escape of vapor into the liquid increases) such a heat-transfer regime should appear with smaller heat loads. This is observed in Fig. 4.

No analogs of the anomalous dependence $a = a(p)$ at the top of Fig. 4b were found in the literature concerning boiling on CPC (the existing investigations were performed, as a rule, at atmospheric pressure).

Thus in this work we obtained data on the characteristics of heat emission accompanying boiling of liquid nitrogen on samples of superconducting ceramic $YBa_2Cu_3O_7$. These data can be used to calculate the conditions under which high-T_c superconductors carrying current are stabilized. We indicated the quantitative and qualitative differences from the case of boiling on smooth metallic surfaces.

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