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EXPERIMENTAL STUDY OF HEAT TRANSFER IN LIQUID-NITROGEN COOLING OF THE SURFACE OF SUPERCONDUCTING $YBa_2Cu_3O_7$ CERAMIC. 2. BURNOUT IN NUCLEATE BOILING

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UDC 536.248.2.001.5

Burnout in the nucleate boiling of nitrogen on flat horizontal metal-oxide ceramic heaters is investigated in the pressure range from $1.3 \cdot 10^4$ Pa to $4.5 \cdot 10^5$ Pa.

We have previously [1] investigated the characteristics of heat transfer in the nucleate boiling of nitrogen on ceramic samples at low to moderate heat flux densities q. Here we give the results of a study of heat transfer at heat inputs approaching burnout, along with the characteristics of nucleate boiling burnout. The first critical (first-stage burnout) heat flux density q_{cr1} and the corresponding differential temperature ΔT_{cr1} are important parameters in calculating the stabilization conditions for current-carrying superconductors cooled by a boiling cryogen [2]. The literature to date does not contain any data on q_{cr1} and ΔT_{cr1} for the boiling of nitrogen on high-temperature superconducting (HTSC) materials. Because of the porous structure and low thermal conductivity λ_N of ceramics [3], these two critical quantities can be assumed to differ from the typical values for boiling on metal surfaces.

The experiments were carried out in a metal cryostat on samples of the superconducting yttrium ceramic $YBa_2Cu_3O_7$ with thicknesses of 3.1 mm and 2.0 mm (samples No. 2 and No. 4 in

Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukrainian SSR, Kharkov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 59, No. 5, pp. 772-775, November, 1990. Original article submitted September 5, 1989.

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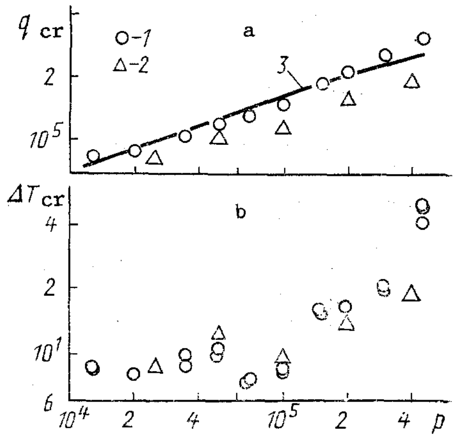

Fig. 1. Characteristics of first-stage burnout vs pressure in the boiling of nitrogen. a) $q_{cr1} = q_{cr1}(p)$; b) $\Delta T_{cr1} = \Delta T_{cr1}(p)$; 1) sample No. 4; 2) No. 2; 3) graph calculated according to Eq. (1) at K = 0.135.

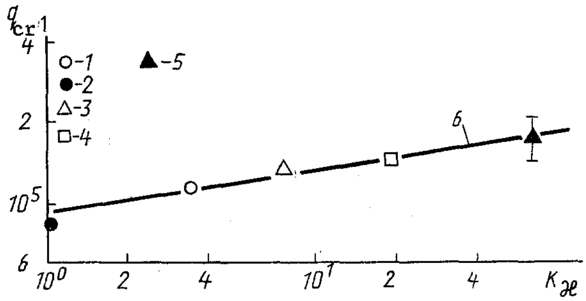

Fig. 2. First critical heat flux density vs ratio of accommodation coefficients of the heater material and nitrogen. 1) Sample No. 2; 2) quartz [7]; 3) steel [6]; 4) nickel [6]; 5) copper [3]; 6) $q_{cr1} \sim K_K^{1/6}$.

[1]) and respective porosities of 16.8% and 28.7%. The heat-transfer surface of the samples was oriented horizontally. The onset of burnout was determined from the sudden rise in temperature of the ceramic as measured by a copper—Constantan differential thermocouple. The centers of the drillholes under the thermocouple were situated at distances of 1.05 mm and 0.65 mm from the heat-transfer surface for samples No. 2 and No. 4, respectively.

Just prior to burnout, the progressive stepped increments of the heat input did not exceed 1% of the previous value of q. In view of the low thermal conductivity of the ceramic, the temperature difference between the heat-transfer surface and the thermocouple station is quite large, amounting to 100 K or more at $q \geq 10^5$ W/m². This value is several times the differential temperature T between the heat-transfer surface and the liquid and therefore provides the main contribution to the error of its determination. Despite the application of such measures as experimental estimation of the thermal conductivity of the ceramic samples and centering of the thermocouple bead in the drill hole [1], the expected error of determination of ΔT_{cr1} was still high: 50-60%. The total expected error of determination of q_{cr1} did not exceed 8%.

The burnout characteristics were determined in experiments at pressures $p = 1.3 \cdot 10^4$ Pa to $4.5 \cdot 10^5$ Pa. When p was increased above this range, the temperature of the heat-releasing element of the heater became too high, and the thermal breakdown of the electrical insulation set in.

The results of the determination of q_{cr1} and ΔT_{cr1} at various pressures are given in Fig. 1. The critical heat flux density increases with the pressure (Fig. 1a); the functional dependence $q_{cr1} = q_{cr1}(p)$ can be described by the equation [4]

$$q_{cr1} = KL\sqrt{\rho_v}\sqrt[4]{\sigma g(\rho - \rho_v)} \qquad (1)$$

with coefficients K = 0.135 and 0.105 for samples No. 2 and No. 4, respectively. Here L is the heat of vaporization, σ is the coefficient of surface tension, g is the gravitational acceleration, and ρ and ρ_v are the densities of the liquid and the vapor.

The relation between heat inputs q_{cr1} obtained on the two samples can be clarified on the basis of the analogy between boiling on the investigated porous ceramic materials and on thick (several millimeters) metal capillary-porous coatings (CPC's). The critical heat flux density for boiling nitrogen on a CPC with 40-93% porosity and a thickness of 0.4-10 mm is known [5] to increase substantially with an increase in the porosity and to decrease only very slightly with an increase in the thickness of the coating. In our case it is evident that the increase in the porosity from 16.8% to 28.7% with a simultaneous decrease in the thickness from 3.1 mm to 2.0 mm did in fact cause q_{cr1} to be larger for sample No. 4 than for No. 2. It is important to note that while the possibilities of nitrogen cooling of a HTSC ceramic can be expanded by increasing the porosity of the samples, the critical burnout current for the sample is lowered at the same time.

In comparing the critical heat flux densities obtained for the yttrium ceramic with the typical values for nitrogen boiling on smooth metal heaters, it is convenient to use the data for sample No. 2, which has a relatively small porosity. In this case it is more correct to determine the dependence of q_{cr1} on the thermophysical properties of the material, as this dependence is not masked by the influence of porosity. Figure 2 shows data on the critical heat flux density for nitrogen boiling under the conditions $p = 10^5$ Pa as a function of the ratio of the accommodation coefficients of the material and the liquid $K_K = \sqrt{(\lambda c\rho)_N/\lambda c\rho}$, where c is the specific heat. The data used here are taken from [6] for nickel and stainless steel and from [7] for quartz; the average value of q_{cr1} obtained in [3] over data from many sources is used for copper. The value of K for the yttrium ceramic sample is taken from [8]. It is evident from Fig. 2 that the value of q_{cr1} for $YBa_2Cu_3O_7$ is in good agreement with the general law.

The first critical differential temperature does not disclose any dependence on the pressure at $p \le 10^5$ Pa, and the values of ΔT_{cr1} for samples No. 2 and No. 4 differ very little from one another (see Fig. 1b). As the pressure is increased above atmospheric, ΔT_{cr1} begins to grow very rapidly; the data for the more porous sample (No. 4) are consistently higher than those for No. 2. This behavior of $\Delta T_{cr1} = \Delta T_{cr1}(p)$ differs from the typical dependence for nitrogen boiling on metal heaters, where the critical differential temperature decreases with increasing pressure [3, 6]. The absolute values of ΔT_{cr1} for the ceramic are much larger than for metals at elevated pressures. The anomalous behavior of $\Delta T_{cr1} = \Delta T_{cr1}(p)$ for $YBa_2Cu_3O_7$ is evidently related to the specific characteristics of heat transfer in the range of heat inputs just prior to burnout (i.e., to the position of the boiling curves), because the experimental values of q_{cr1} strongly favor a predominantly hydrodynamic burnout mechanism.

In the first part of the article we mentioned a significant difference in heat transfer during the boiling of nitrogen on ceramic samples at high values of q from boiling on metal heaters, in particular, the agreement of the boiling curves obtained at different pressures $p > 10^5$ Pa [1]. Data on the boiling of nitrogen on sample No. 4 at subcritical (before burnout) heat inputs are shown in Fig. 3, where they lend corroboration to the above-indicated tendencies. The boiling curves merge at $p \ge 1.5 \cdot 10^5$ Pa, and an increase in the pressure merely has the effect of extending the general dependence $q = q(\Delta T)$ to large differential temperatures because of the growth of q_{cr1} (see Fig. 3b; the upper points of each curve in Fig. 3 correspond to the conditions of nucleate boiling burnout). Moreover, the slope of the $q = q(\Delta T)$ curve decreases. The decrease in the slope of the curve is greatest at $p = 4.5 \cdot 10^5$ Pa in the case where the differential temperature exceeds $\Delta T \approx 20$ K; this value is close to the limiting superheat of liquid nitrogen at the given pressure [3]. Apparently, "scalded" zones occur on the heat-transfer surface in the interval $q = (2.8\text{-}3.05) \cdot 10^5$ W/m^2 (and they exist in the depth of the porous sample at smaller heat inputs [1]). At $p \le 10^5$ Pa the segregation of the data according to pressure and the actual shape of the $q = q(\Delta T)$ curves are typical of boiling on smooth metal heaters (Fig. 3a).

Boiling curves with a similar shape, extending into the range of large differential temperatures, are typical of nitrogen boiling on a very thick CPC [9, 10]. It is also a well-known fact that ΔT_{cr1} increases with the porosity of the CPC [5]. This behavior also appears to account for the higher critical differential temperatures obtained on the ceramic

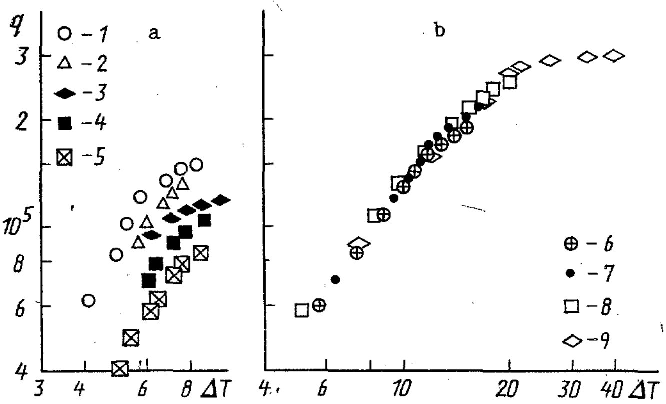

Fig. 3. Plots of $q = q(\Delta T)$ for nitrogen boiling on sample No. 4 in the presence of lowered (a) and elevated (b) pressures. 1) $p = 1 \cdot 10^5$ Pa; 2) $7 \cdot 10^4$; 3) $5 \cdot 10^4$; 4) $3.5 \cdot 10^4$; 5) $1.3 \cdot 10^4$; 6) $1.5 \cdot 10^5$; 7) $2 \cdot 10^5$; 8) $3 \cdot 10^5$; 9) $4.5 \cdot 10^5$ Pa.

sample No. 4 (see Fig. 1b). The behavior of $\Delta T_{cr1} = \Delta T_{cr1}(p)$ at elevated pressures is similar to that of $q_{cr1} = q_{cr1}(p)$, because the $q = q(\Delta T)$ curves are not segregated according to pressure, and the relation between q and ΔT at subcritical heat inputs is linear on the average.

Consequently, these data indicate that the critical heat flux densities for nitrogen boiling on HTSC ceramic samples are somewhat lower, while the critical differential temperatures are much higher than in boiling on metal heaters. The functional dependence $q_{cr1} = q_{cr1}(p)$ can be described by the well known Kutateladze relation, and the dependence $\Delta T_{cr1} = \Delta T_{cr1}(p)$ exhibits an anomalous behavior. The quantities q_{cr1} and ΔT_{cr1} depend on the porosity and thickness of the ceramic samples in qualitatively the same way as for nitrogen boiling on CPC. The results of the study can be utilized in calculating the thermal stabilization of high-temperature current-carrying superconductors cooled by liquid nitrogen with free flow of the cryogen.

The authors are grateful to V. T. Zagoskin for preparing the superconducting yttrium ceramic samples and to O. S. Komarevskii for assistance with the experiments.

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