In conclusion, we studied superconducting and amorphous materials with compositions $YBa_2Cu_3O_x$ and $Bi_2Sr_2CaCu_2O_y$. Certain regularities that allow for the determination of thermodynamically similar points in high-temperature superconductors were discovered. We proposed a thermodynamic criterion bounding the existence region of high-temperature superconductivity.

NOTATION

T, absolute temperature; $\rho(T)$, electrical resistivity; $\chi(T)$, magnetic susceptibility; T_c, superconducting transition temperature; c_p, specific heat capacity at constant pressure; T_K, Kauzman temperature; Θ, Debye temperature.

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HEAT EXCHANGE DURING THE BOILING OF HELIUM ON THE SURFACE OF $YBa_2Cu_3O_7$ HTSC-CERAMIC

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UDC 536.248.2.001.5

We investigate the heat transfer and crises in the nucleate and film boiling of helium on flat metal-oxide ceramic heaters at pressures 0.006-0.165 MPa.

In [1-2] we investigated heat transfer characteristics during the boiling of nitrogen on the surfaces of high-temperature superconducting $YBa_2Cu_3O_7$ ceramic samples. There are grounds for thinking that high-temperature superconductors (HTSC) with very large upper critical magnetic fields might be used efficiently at helium temperatures, for example, for current leads [3, 4] and for the solenoid windings of superconducting magnetic systems for fields above 20 T [5]. For these reasons the determination of the heat exchange characteristics of HTSC ceramics with liquid helium is of interest. The critical current density of modern HTSC-conductors at T = 4.2 K exceeds 10^5 A/cm^2, and the significant level of heat release during the transition to the normal state makes the heat transfer crisis the primary objective of our investigation. Depending on the technique used for the preparation of composite current-carrying components, the superconductor might either be in direct contact with the cryogenic medium or be separated from it by a sheath made of a normal metal; the present investigation is applicable to the first case.

The experiment was carried out inside a glass Dewar flask at pressures between 0.006 and 0.165 MPa. In the study we used $YBa_2Cu_3O_7$ HTSC ceramic samples which were 14 mm in diameter, 7-mm thick, and thermally insulated and an electric heater with three thermocouples; the sample design is the same as described in Baranets et al. [1, 2]. Due to the low thermal conductivity of HTSC-ceramics [6] for $q \geq 10^3$ W/m^2, the internal temperature of the samples was sufficiently high, which allowed us to use copper—constantan thermocouples in order to determine the temperature. The temperature of heat transfering surfaces was found by extrapolation. Experiments were conducted on four samples with volume porosities between 10% and

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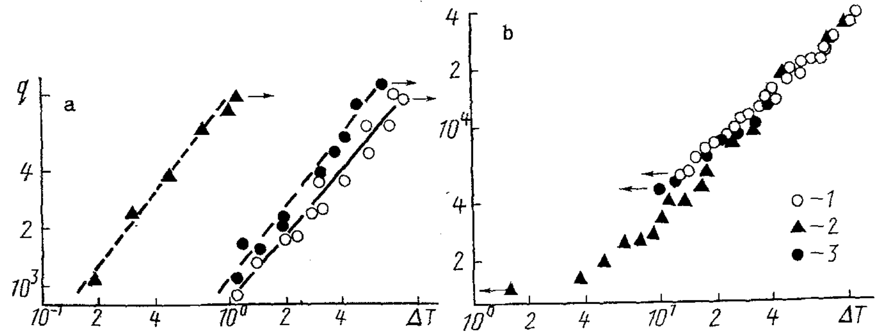

Fig. 1. $q = q(\Delta T)$ dependence during (a) the nucleate and (b) the film boiling of helium at atmospheric pressure on 1) HTSC ceramic; 2) copper; and 3) steel. The arrows indicate heat transfer crises. q in W/m^2 and ΔT in K.

30%. The measuring system and the experimental method were essentially the same as those used by Baranets et al. [1, 2], except that during the helium boiling process we were able to study in detail the film boiling mode. The first and second heat transfer crises were located using the quasi-stationary method. Within each boiling regime, a small change in the heat current supplied by the electric heater was accompanied by a small change in sample temperature; however, in passing from one regime to another (i.e., crisis) for a small change in heat q the sample temperature T_H changed sharply. A uniform heating of the heat transferring surface, the small diameter (0.3 mm) of the leads for the independent electric heater, and a reliable heat insulation ensured that the surface of the boiling surface was isothermal and prevented the boiling film from prematurely coming off.

The estimated error in the determination of the heat flux density, including the heat leakage through the insulation, increased overall from 8% at $q = 10^3$ W/m^2 to almost 20% at the maximum attained heat load level of $q = 4 \cdot 10^4$ W/m^2; however, the error reached a minimum at the nucleate boiling crisis. The corresponding error in the determination of the differential temperature increased from 25% at $q = 10^3$ W/m^2 to 55% at $q = q_{cr1}$, but a further increase in the heat flux density (in the film boiling mode) did not lead to the growth in the relative error because of an enhancement in the sensitivity of the thermocouple and the large absolute values of ΔT.

Figure 1 shows the data obtained in the present work on the boiling of helium at atmospheric pressure on the surface of one of the HTSC samples as well as the data for several large metallic heaters from [7] for both the film and nucleate boiling modes. Clearly, during film boiling the properties of the heater material have no effect on the location of the curve $q = q(\Delta T)$; however, the film boiling crisis for helium on HTSC occurs for larger values of q and ΔT than it does for metals. During the nucleate boiling of helium, there is a significant difference between the results obtained for HTSC and copper, while the difference between the results for HTSC and steel is small. For similar $q = q(\Delta T)$ dependences, the heat transfer rate on ceramic surfaces is lower in comparison with metals. The position of the first heat transfer crisis point is displaced to the right toward the region of high differential temperatures; however, the value of $q = q_{cr1}$ stays at approximately the same level, without undergoing a regular change.

The dependence of the heat transfer coefficient $\alpha = q/\Delta T$ on the heat assimilation coefficient for the heater material during nucleate boiling may be estimated from the data in Fig. 1 after calculating K_c for the HTSC. Assuming that at $T = 4.2$ K the average value of $\lambda_H = 0.3$ $W/(m \cdot K)$ [6], $c_H = 0.3$ $J/(kg \cdot K)$ [8], and $\rho_H = 6.35 \cdot 10^3$ kg/m^3, we obtain $\sqrt{(\lambda c \rho)_H} = 23.9$ $W \cdot sec^{0.5}/(m^2 \cdot K)$ and $K_c = 0.216$. Then to a first approximation $\alpha \sim K_c^{0.7}$ in the range $K_c = 0.216-4$. This dependence is somewhat weaker than is typical for metallic heaters, for which $\alpha \sim K_c^{0.5}$ [9].

It should be noted that during the boiling of nitrogen on ceramic and copper heaters no appreciable differences in thermal transfer coefficients are observed: the boiling curves $q = q(\Delta T)$ intersect one another, and, if for $q \geq 5 \cdot 10^4$ W/m^2 the heat transfer rate is higher for copper surfaces, then for $q < 5 \cdot 10^4$ W/m^2 it is higher for HTSC-ceramic surfaces [1].

During the nucleate boiling of helium we were not able to discover a noticeable influence of pressure (in the range $p = 0.023-0.15$ MPa) on the magnitude of α, at least for $q \geq 10^3$ W/m^2.

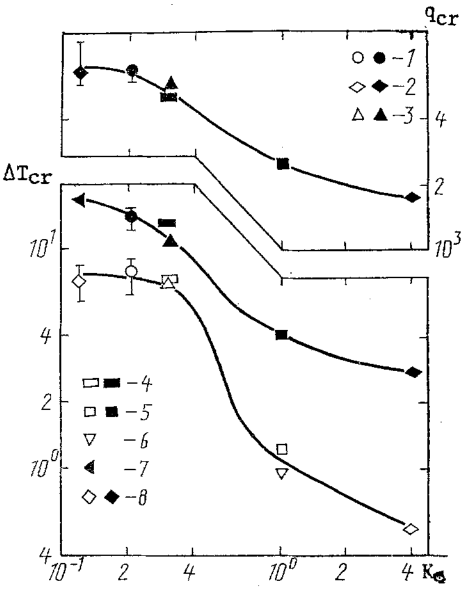

Fig. 2. Dependence of the helium boiling crisis curves at atmospheric pressure on the ratio of the heat assimilation coefficients of the heater material to that of the liquid: 1) HTSC ceramic; 2) copper [9]; 3) steel [9, 10]; 4) steel [7, 11]; 5) AMr alloy [9, 10]; 6) brass [11]; 7) BF-2 glue [12]; 8) varnish, paint, and fluoroplast [12, 13]. Open symbols) the first boiling crisis; filled symbols) the second boiling crisis. q_{cr} in W/m²; ΔT_{cr} in K.

This fact agrees qualitatively with previous results regarding boiling on the surfaces of large steel heaters [9, 10], where it was found that the growth of α with increasing pressure was insignificant in comparison with the typical behavior for copper, which confirms the tendency of the dependence $\alpha = \alpha(p)$ to weaken with decreasing K_c.

However, during the film boiling of helium on HTSC samples, the situation is reversed: the heat transfer coefficient was found to change with pressure. In the range from $p = 0.006$ to 0.1 MPa, α increases on the average of 1.7 times; a further increase of pressure has a small effect on the thermal transfer coefficient. These results agree well with the existing data on the boiling of helium on metal heaters [9].

The dependence of q_{cr2}, ΔT_{cr1}, and ΔT_{cr2} on the total K_c is shown in Fig. 2, where together with HTSC-ceramics other metallic and nonmetallic materials are included. The data on q_{cr1} are not given since the first critical heat flux density is approximately similar for HTSC (on the average equal to $9.2 \cdot 10^3$ W/m²) and for copper (according to the averaged data of several investigators [9] $\bar{q}_{cr1} = 9.36 \cdot 10^3$ W/m²) and, consequently, does not depend on K_c. The remaining properties of the crises, as evident from Fig. 2, change by almost an order of magnitude. For copper, the averaged results obtained in [9] are provided; the set of points 7 and 8 are for metallic surfaces covered with a layer of glue, varnish, paint, or other dielectrics [12, 13]. The curves were drawn to aid the eye. Thus, HTSC-ceramics do not violate the general dependence, and their behavior is intermediate between low-thermal conductivity metallic alloys (steel) and organic dielectrics. The increase of the crisis curves in going from copper to ceramics is very substantial, growing 3-4 times for q_{cr2} and almost 15 times for ΔT_{cr1}.

The pressure dependence of the thermal transfer crisis characteristics during the boiling of helium is shown in Fig. 3, where the data for a number of HTSC samples are shown in order to compare their reduced values. The comparison of the $q_{cr1,2}$ data with the values calculated using C. C. Kutateladze's formula [14] shows that, just as in the case of the boiling of helium on metal surfaces, the calculated values underestimate the measured values of $q_{cr1,2}$ for $p < 0.1$ MPa and overestimated them for $p > 0.1$ MPa. A better agreement is obtained with the empirical expression [15],

$$\tilde{q}_{cr} = 0{,}276 + 7{,}52\,(p/p_c) - 27{,}1\,(p/p_c)^2 + 47{,}6\,(p/p_c)^3 - 44{,}0\,(p/p_c)^4 + 15{,}7\,(p/p_c)^5, \tag{1}$$

TABLE 1. Boiling Crisis Characteristics of Nitrogen and Helium on Ceramic and Copper Heaters

Heater material	Cryogen	q_{cr1}, kW/m^2	ΔT_{cr1}, K	q_{cr2}, kW/m^2	ΔT_{cr2}, K
$YBa_2Cu_3O_7$ [1, 2, 18, 19]	Nitrogen	115—145	8,5—18,0	22—34	100—140
	Helium	8,8—9,6	6,0—8,8	5,6—6,9	12,0—14,7
Copper [17]	Nitrogen	177	6,3	15	27
	Helim	9,36	0,52	1,72	2,54

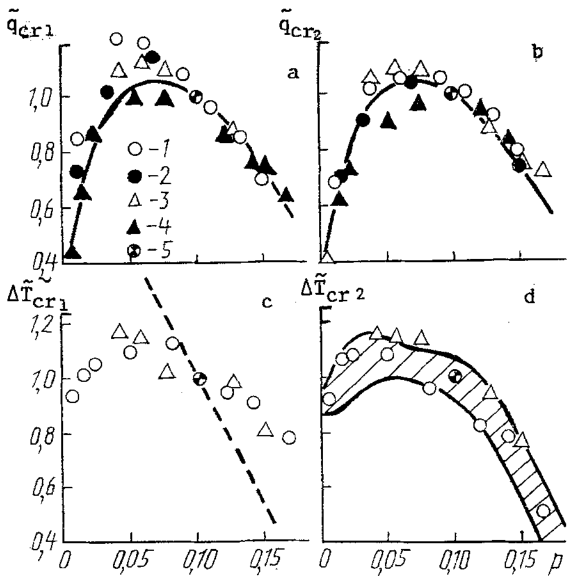

Fig. 3. Pressure dependence of the reported values of crisis characteristics for helium boiling on HTSC-ceramics: a) $\tilde{q}_{cr1} = \tilde{q}_{cr1}(p)$; b) $\tilde{q}_{cr2} = \tilde{q}_{cr2}(p)$; c) $\Delta\tilde{T}_{cr1} = \Delta\tilde{T}_{cr1}(p)$; c) $\Delta\tilde{T}_{cr2} = \Delta T_{cr2}(p)$; samples with porosities of 1) 10%; 2) 17%; 3) 29.4%; 4) 35%; 5) $\tilde{q}_{cr} = 1$ and $\Delta\tilde{T}_{cr} = 1$; continuous curve) calculated according to Eq. 2; shaded region) the data obtained on metallic heaters [9]. p in MPa.

which combines well the measured values of different authors [9]. The curves calculated according to Eq. 1 are shown in Fig. 3a and b. According to these curves, the dependence of $q_{cr1,2} = q_{cr1,2}(p)$ for helium boiling on HTSC is almost the same as that observed for boiling on metallic heaters. These curves attain their maximum in the region p = 0.06-0.08 MPa.

Figs. 3c and d for critical differential temperatures are overall qualitatively similar to the dependence $\tilde{q}_{cr} = \tilde{q}_{cr}(p)$, but their maxima are shifted slightly to the left (p = 0.05 MPa), and the decrease of ΔT_{cr} with decreasing pressures is less rapid. For metallic heaters ΔT_{cr1} typically varies monotonically with an increasing p; the line in Fig. 3c is a generalization of most of the known data [9]:

$$\Delta\tilde{T}_{cr1} = 2{,}09\,(1 - p/p_c)^{1,3}. \tag{2}$$

This line departs noticeably from the data on HTSC samples; however, the dependence $\Delta T_{cr1} = \Delta T_{cr1}(p)$ exhibiting a maximum was obtained in [16] on a large steel heater.

The pressure dependence of the second critical differential temperature for ceramics agrees well with the majority of known results for metallic heaters. Figure 3d shows the region together with the data obtained by several authors and collected in [9].

Accordingly, the values of heat transfer characteristics for the boiling of helium on the surfaces of HTSC samples in most cases strongly differ from the typical values for helium boiling on copper (except for the magnitude of q_{cr1} and the heat transfer during film boiling); however, this difference in the case of the values measured during boiling on large steel heaters is quite insignificant. The latter is due to the comparatively small difference between the value of K_c for HTSC (≈0.22) and for steel (≈0.35), while at the same time $K_c \approx 4$ for copper. The independence of such characteristics as q_{cr1} and α during helium film boiling from the thermophysical properties of the heater material is mainly determined by the hydrodynamic nature of the processes that characterize them.

Regarding the cryostabilization of the superconducting state in ceramic superconductors through which a current passes, the question arises: at what temperature — liquid nitrogen or liquid helium — is there a more significant difference between the heat transfer characteristics of HTSC and of copper during boiling on their surfaces? The table below provides some values of $q_{cr1,2}$ and $\Delta T_{cr1,2}$.

The present results indicate that during helium cooling of high-temperature superconductors without a metallic sheath (matrix) the heat transfer properties may differ strongly from those of copper surfaces which are commonly used in cryostabilization designs. The use of actual values of α, q_{cr2}, and $\Delta T_{cr1,2}$ for HTSC-ceramics would significantly improve such designs which are indispensable in the fabrication of helium-cooled magnetic superconducting systems that are rated for fields higher than 20 T.

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NOTATION

c, heat capacity, J/(kg·K); $K_c = \sqrt{(\lambda c\rho)_H/(\lambda c\rho)_\ell}$; q, heat flux density, W/m^2; p, pressure, MPa; p_c, critical pressure, MPa; T, temperature, K; ΔT, differential temperature, K; α, heat transfer coefficient, W/(m^2·K); λ, thermal conductivity, W/(m·K); ρ, density, kg/m^3; indices: cr1, first heat transfer crisis; cr2, second heat transfer crisis; H, heater; ~, reduced value.

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ON CALCULATION OF HEAT EXCHANGE FOR CONDENSATION IN HORIZONTAL TUBES

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A method is proposed for determining the intensity of condensation from the value of the equivalent force applied to the condensate film. The asymmetry of film flow along the perimeter of a horizontal tube and the dependence of the characteristic size of the calculation expressions on regime parameters of the condensing flow are demonstrated.

Heat exchange devices using condensation within horizontal tubes are found in many branches of industry. Despite this fact, the heat liberation conditions for such devices have not been studied sufficiently. An analysis of available data [1] shows that for one and the same range of condensing flow regime parameters the calculation expressions presented produce qualitative and quantitative divergences in the principles of heat exchange. The most significant divergences occur in calculated heat liberation coefficients in the range of moderate and low motion velocities and with complete condensation of the vapor. The absence of reliable engineering and theoretical computation equations is retarding the wide use of efficient horizontal heat exchange apparatus.

The causes for the existing divergence in calculation expressions for a comparable thermal flux density range [2-9] were partially analyzed in [1]. The author explained their existence by change in flow regimes of the phases along tube length, neglect of the size of the condensate stream, change in the film flow regime, which can be turbulent over a portion of the tube length. However, it should be considered that within the horizontal tube the force of gravity is perpendicular to the direction of vapor flow, and not aligned thereto, as in vertical tubes and the outer surface of horizontal tubes. This fact changes the film hydrodynamics and principles of heat exchange significantly.

The studies of local heat exchange performed in [10, 11] permitted establishment of some principles of film hydrodynamics within a horizontal tube. Analysis of data on local heat exchange shows that asymmetry of the film condensate thickness along the perimeter of the horizontal tube beginning with its initial segment is intrinsic to the flow of a two-phase medium (Fig. 1a). This effect intensifies with increase in condensation and thermal flux density (thick films) as indicated by the data shown in Fig. 1b. Moreover, significant removal of liquid into the vapor flow, possibly reaching 80%, is inherent to the process of moving vapor condensation [10].

Comparison of experimental values of the heat liberation coefficient (Fig. 2), obtained in a segment $\ell = 0.04$ m long with values calculated from the Nusselt dependence for conditions where the tube position in space has no effect on heat exchange [12], and for the case of dominant friction forces and turbulent film flow [13] shows that the numerical values of the mean heat liberation coefficients on the perimeter of the horizontal tube $\bar{\alpha}_\varphi$ are higher than calculated in all cases. Such a result is the consequence of flow of the condensate film on the lower tube directrix into the condensate stream zone, which increases the intensity of the process on the remaining portion of the perimeter. In turn this feature of the film hydrodynamics causes the condensate in its motion on the lower directrix to traverse a

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