Journal of Engineering Physics and Thermophysics, Vol. 67, No. 3-4, 1994

HEAT TRANSFER OF HTSC-CERAMIC COOLED BY LIQUID HYDROGEN

I. M. Kolod'ko, N. M. Levchenko,
S. V. Nozdrin, K. V. Rusinov, and
E. G. Tyurina

UDC 536.248.2.001.5

An experimental investigation of heat transfer and crises of bubble and film boiling of hydrogen on the $YBa_2Cu_3O_7$ HTSC-ceramic is described. Heat transfer characteristics obtained at pressures from 17 to 100 kPa and heat flux densities from 0.1 to 120 kW/m^2 are compared with well-known results for hydrogen boiling on metal heaters.

According to some estimates, the efficiency of superconducting magnetic systems based on high-temperature superconductors (HTSC) may reach a maximum if they are cooled to temperatures of 20–30 K. The favorable combination of characteristics, compared to nitrogen and helium levels of cooling, is attained due to the fact that the hydrogen system of cryostatting consumes much less energy than the helium one, whereas the critical current density in the HTSC-wire at 20–30 K remains rather high and almost insensitive to the action of a magnetic field; this has not been achieved as yet with nitrogen cooling. Moreover, it is shown in [1, 2] that the optimum working temperature of the adiabatic winding of a magnetic system with regard to the criterion of the restriction on the maximum heating with a complete loss of superconductivity amounts to 20 K.

In this connection it is of interest to determine the main features of heat transfer in boiling of hydrogen on an HTSC-ceramic: points of the start of boiling and the first and second crises of heat transfer and curves of bubble and film boiling. So far, such data are lacking in the literature. Investigations of heat transfer of nitrogen [3, 4] and helium [5] boiling on the surface of an HTSC-ceramic showed that the position of the boiling curves $q = q(\Delta T)$ for this material differs substantially from that typical of boiling on metals with a high thermal conductivity (copper etc.).

In our experiments we used four $YBa_2Cu_3O_7$ HTSC-ceramic samples produced by cold pressing of powder with subsequent heat treatment (for further details see [3–5]). Three samples had the shape of a disk and one of a rectangular plate; the dimensions of the samples are presented in Table 1. The design of the experimental blocks is described in detail in [3–5]. Two blocks were equipped with germanium resistance thermometers. This permitted us to obtain reliable results in the region of small heat flux densities. At high values of q the temperature of the ceramic increases sharply and the sensitivity of the thermometers decreases rapidly, and therefore the main volume of data in this region was obtained on two blocks with copper-constantan thermocouples. In samples Nos. 1 and 3 temperature sensors were located along the heat flux direction, and this made it possible, first, to determine the temperature gradient and the effective heat conduction coefficient of the ceramic and, second, by using extrapolation, to obtain the temperature of the heat-releasing surface, which is needed for calculating the thermal head. The values of λ were used to calculate the values of T_r on "thin" samples (Nos. 2 and 4). Sample No. 4 had six thermocouples equidistant from the heat-releasing surface; here the thermal head was calculated from the arithmetic mean value of T_r.

The experiments were carried out at atmospheric pressure and at a pressure of 17 kPa, which was maintained by drawing away hydrogen vapors by an NVZ-20 pump. A Dewar glass flask made it possible to determine visually the instant of the start of liquid boiling on the heat-releasing surface of the samples and the

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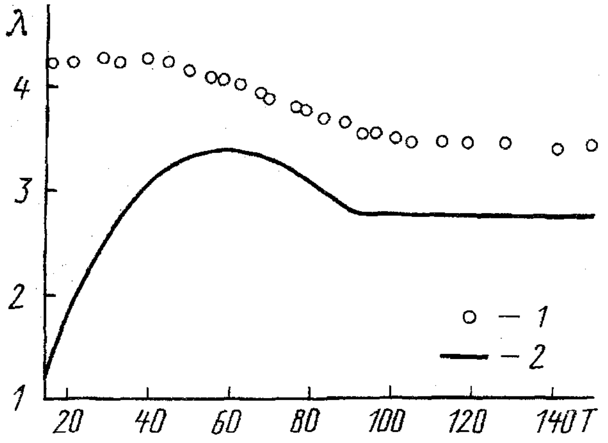
Physicotechnical Institute of Low Temperatures, Academy of Sciences of the Ukraine, Khar'kov. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 67, Nos. 3-4, pp. 179-183, September-October, 1994. Original article submitted March 15, 1993.

1062-0125/94/6734-0837$12.50 ©1995 Plenum Publishing Corporation

TABLE 1. Characteristics of the HTSC-Ceramic Samples

No. of sample	Dimensions of heat-releasing surface, mm	Thickness, mm	Porosity, %	Temperature sensors		Orientation of heat-releasing surface
				type	quantity	
1	⌀19.4	15.2	21.6	Resistance thermometers	2	Horizontal
2	⌀19.7	6.4	22.4	"	1	"
3	⌀15.0	15.0	20.9	Thermocouples	5	"
4	29.5× 8.0	2.0	22.0	"	6	Vertical



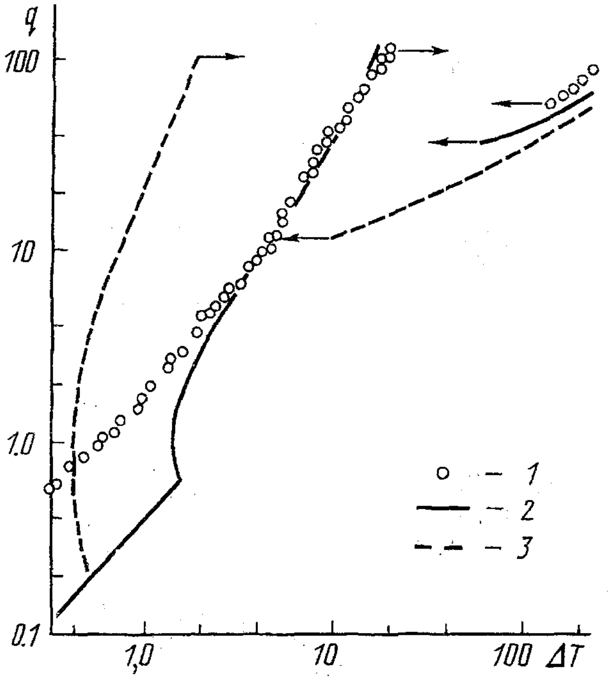


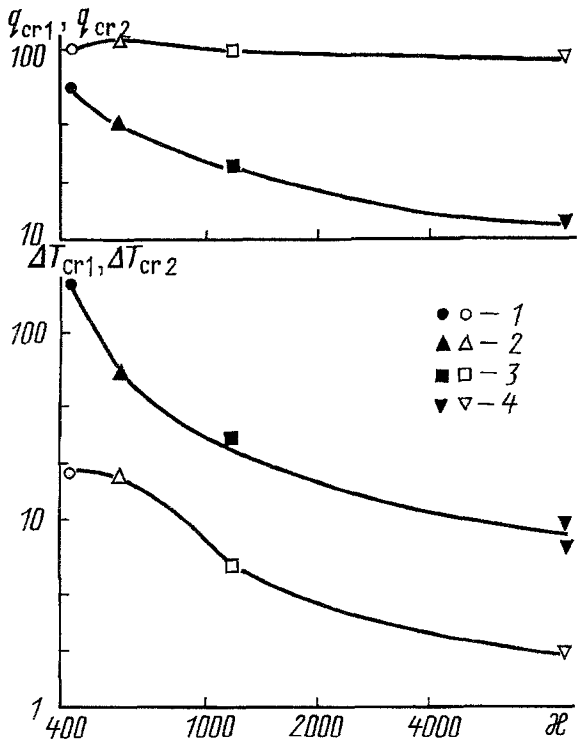
Fig. 1. Dependence of the thermal conductivity coefficient of the HTSC-ceramic on temperature: 1) effective thermal conductivity of samples Nos. 1 and 3; 2) thermal conductivity of HTSC-ceramic with evacuated pores [7]. λ, W/(m·K); T, K.

Fig. 2. Dependence of the heat flux density on thermal head for hydrogen boiling at atmospheric pressure: 1) HTSC-ceramic; 2) steel [6]; 3) copper [6]. q, kW/m^2; ΔT, K.

corresponding values of q_0 and ΔT_0. The q_{cr1}, q_{cr2}, ΔT_{cr1}, and ΔT_{cr2} values for heat transfer crises were determined by the quasistationary method on the "thin" sample No. 4. This sample was also used for investigating the film boiling of hydrogen.

The results obtained in the present work were compared with the heat transfer characteristics of hydrogen boiling on metal heaters made of copper, steel, etc.; the most complete data pertaining to this case are contained in [6].

In Fig. 1 the dependence of the effective thermal conductivity coefficient of samples Nos. 1 and 3 on the temperature of the ceramic is compared with data on the thermal conductivity of an HTSC-ceramic with evacuated pores [7] whose porosity is close to that of the samples. It is seen that, as the temperature decreases below 60K, the contribution of the intrapore processes of convection and evaporation to the overall heat transfer increases



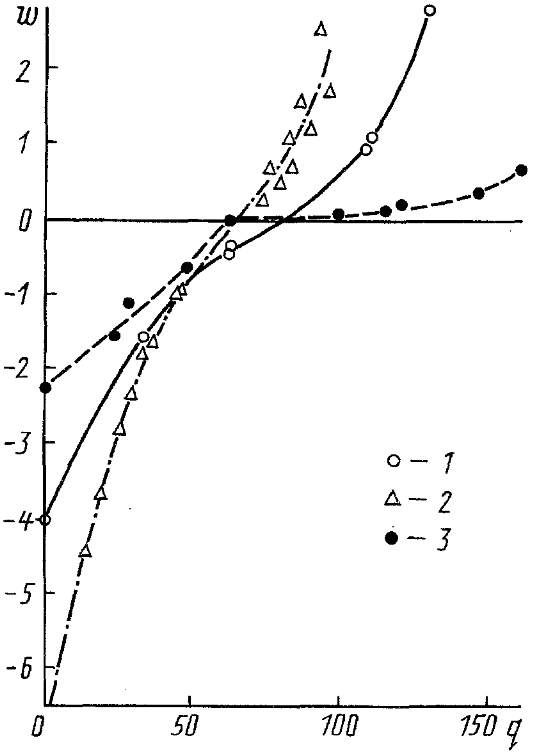


Fig. 3. Dependence of the characteristics of heat transfer crises of hydrogen boiling at atmospheric pressure on the coefficient of heat assimilation of the heater material: 1) HTSC-ceramic; 2) steel [6]; 3) AMg-5 alloy [6]; 4) copper [6]; open symbols, first of heat transfer; filled symbols, second crisis of heat transfer. q_{cr1}, q_{cr2}, kW/m^2; ΔT_{cr1}, ΔT_{cr2}, K; κ, W·sec$^{0.5}$/(m^2·K).

Fig. 4. Dependence of the TAW front velocity during change in boiling regimes at atmospheric pressure on the heat flux density: 1) hydrogen on HTSC-ceramic; 2) hydrogen on steel [10]; 3) nitrogen on HTSC-ceramic [4]. w, mm/sec.

rapidly and becomes decisive, whereas the conduction component of heat transfer (i.e., heat conduction along the skeletal frame of the porous structure) ceases to play a significant role.

A typical curve of the bubble and film boiling of hydrogen on the HTSC-ceramic is presented in Fig. 2; the arrows denote the points of the heat transfer crises. For purposes of comparison, we present data on the boiling of hydrogen on copper and stainless steel [6]. The first vapor bubbles appear on the surface of the ceramic at nearly the same values of the heat flux density q_0 as on the metal heaters (0.25–2.0 kW/m^2); however, the thermal heads corresponding to the start of boiling on the ceramic turn out to be much smaller and their lower boundary ($\leq$ 0.3 K) lies within the limits of the computational error in determining the value of ΔT_0. The upper boundary corresponds to the values $\Delta T_0 \approx 1.0$ K. A change in the pressure did not exert an appreciable effect on q_0 or ΔT_0, and the variation of these quantities in repeated experiments and from sample to sample was greater than the effect of pumping.

In the case of developed bubble boiling of hydrogen ($q \geq 7$ kW/m^2) the data obtained on the HTSC-ceramic agree rather well with the results of experiments on a massive steel heater. At the same time, at small heat fluxes and thermal heads for the ceramic are smaller than for steel heaters, and when $q < 0.8$ kW/m^2 they are smaller than for copper heaters. The elevated intensity of heat transfer in this region of heat fluxes is explained by the porous structure of the HTSC-ceramic, which facilitates the start of boiling and evaporation in the interior of the sample [8]. In the case of developed boiling, when the processes occurring on the outer heat-releasing surface of the sample play the crucial role, the decisive factor is the heat assimilation coefficient of the heater material, with decrease of which the heat transfer rate decreases [8]. If for calculations we use the effective thermal conductivity coefficient from Fig. 1 and the heat capacity according to the data of [9], then the value of the heat assimilation coefficient of the HTSC-ceramic will turn out to be rather close to the corresponding value for steel but much smaller than for copper (see Fig. 3). This seems to explain the coincidence of the curves for developed bubble boiling of hydrogen on poorly conducting materials (steel and ceramic) and the low heat transfer rate compared to boiling on copper.

The results obtained for bubble boiling under conditions of reduced pressure (p = 17 kPa) point to an insignificant displacement of the boiling curve $q = q(\Delta T)$ to the right; the thermal heads exceed the ΔT values (p = 100 kPa) by no more than 10% at the same heat flux densities.

In the mode of the film boiling of hydrogen the curves $q = q(\Delta T)$ do not reveal a noticeable effect of the properties of the heater material beyond the limits of the near-critical region of the values of ΔT. At the same time the critical point q_{cr2}, ΔT_{cr2} is greatly displaced to the side of large thermal heads with respect to the critical points for the boiling of hydrogen on copper and steel. In the first heat transfer crisis the q_{cr1} value depends little on κ, whereas the critical thermal head ΔT_{cr1} increases with a decrease in the heat assimilation coefficient of the heater material.

The dependences of the critical characteristics of the boiling of hydrogen on κ are compared in Fig. 3. Just as in the case of the boiling crises for nitrogen and helium [3–5], the data obtained on the HTSC-ceramic agree satisfactorily with the results for boiling on metal heaters, compasing a general dependence on the heat assimilation coefficient. At p = 17 kPa, for the ceramic q_{cr1} = 54 kW/m^2 and ΔT_{cr1} = 10.5 K.

The velocity of the front of the temperature autowave (TAW) during the change in the boiling modes on the occurrence of crisis also represents an important characteristic of thermal processes and depends on the thermophysical properties of both the heater material and the cryogenic agent [4, 10]. The results of the determination of the value of w for hydrogen boiling on sample No. 4 are presented in Fig. 4; here $w > 0$ corresponds to the first heat transfer crisis and $w < 0$ to the second (i.e., to the descent of the vapor film). It is seen that the dependence $w = w(q)$ for the HTSC-ceramic has a character similar to that of the data for a steel heater [10]; however, at the same values of q the values of w for the ceramic are much smaller. Moreover, the equilibrium value of the heat flux density, at which the boiling regimes coexist stably on the heat-releasing surface (w = 0), are higher for the ceramic than for steel. Points 3 in Fig. 4 correspond to the results for the TAW front velocity on sample No. 4 but for the boiling of nitrogen. It is seen that transisition to a high-boiling cryogenic agent leads to a substantial decrease in the rate of change of the boiling regimes on the HTSC-ceramic; this is associated with rapid growth of the heat capacity with rise in temperature.

Thus, as a result of an experimental investigation we determined the basic characteristics of hydrogen boiling on the $YBa_2Cu_3O_7$ HTSC-ceramic and established the place of the HTSC-ceramic in the general dependences of these characteristics on the thermophysical properties of the heater materials. The data obtained can be used for calculating the regimes of cryostatting of HTSC-based superconducting magnetic systems cooled by liquid hydrogen.

NOTATION

c, mass heat capacity of ceramic at constant pressure; q, heat flux density; T, temperature of ceramic; $\Delta T = T_r - T_{liq}$, thermal gead; w, linear velocity of TAW front; $\kappa = \sqrt{\lambda c \rho}$, coefficient of heat assimilation; λ, effective thermal conductivity coefficient of ceramic; ρ, density of ceramic. Subscripts: liq, liquid; cr1, cr2, first and second crisis of heat transfer, respectively; r, heat-releasing surface; 0, start of boiling of liquid.

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