EFFECT OF ELECTRICAL INSULATION COATING ON THERMAL STATE OF SUPERCONDUCTING BUSBARS

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It is demonstrated, on the basis of experimental data, that a high thermal resistance of the coating can facilitate transition of a superconductor to the normal state with attendant release of heat in amounts below the first critical level.

It is well known that during ac operation of superconductor devices, there evolves Joule-effect heat in the conductor which must be carried away by a circulating coolant. Therefore, one of the main problems to be solved in the planning, design, and operation of superconductor devices is to reliably ensure cryostatization of the winding conductors at the helium temperature level. However, stable maintenance of the operating temperature of a superconductor depends on many factors such as character and level of heat transfer from the winding conductors, material and thickness of the electrical insulation coating, structural features of the superconductor device, coolant operating parameters, etc.

Particularly important in this regard would be an experimental study of the effect of electrical insulation coatings on the temperature of heat generating superconductors under such coatings, as the thermal flux transferred to boiling helium varies. The need for such a study is dictated, firstly, by the unavailability of sufficiently reliable data on the thermal conductivity of most electrical insulation materials used in cryoelectrical engineering [1-3] and, secondly, the lack of published references on the dependence of the heat transfer coefficient on the structure and the thickness of coating material, its thermophysical properties, and the technology of the coating process. Because of this lack of data, it is now very difficult to calculate the conductor temperature, on which the operating and critical performance parameters of a superconductor device depend.

There have been made some studies [4-9] of the heat transfer during boiling of liquid helium at coated surfaces. In the study made by A. P. Butler et al. [4] the experimental device consisted of two 5 mm thick vertical copper plates with a heater and a temperature probe fastened in the gap between them. The heat emitting surfaces of these plates were clad with organic coatings of various thicknesses. The experimental data of this study [4] indicate that the dependence of the specific thermal flux q on the temperature difference ΔT between that at the substrate surface under the coating (T_u) and that of the coolant in the state of saturation (T_s) is depicted by a curve shifted toward larger temperature differences ΔT relative to the analogous curve for the case of helium boiling at an uncoated surface. Similar results have been obtained in another study [5] with an about 40 μm thick layer of vaseline deposited on a vertical tube heated by electric current and in still another study [6] dealing with the effect of a layer of organic dye deposited on the base surface of a platinum cylinder.

A study was also made [7] of the effect of a triple-layer coating (two layers of Terylene, 20 μm thick each, and 80-μm-thick glass tape impregnated with epoxy resin) on the temperature of a superconductor under the coating cooled by boiling helium. The active element here consisted of two transposed superconductors with a heater placed between them. According to the test results, the temperature drop between superconductor and coolant is more than one order of magnitude larger than in the case of cooling an uncoated conductor with boiling helium under the same thermal flux as a coated one over the entire range of heat loads.

Thus published data indicate that the high thermal resistance of a poorly conducting coating can cause appreciable heating of the metal substrate underneath.

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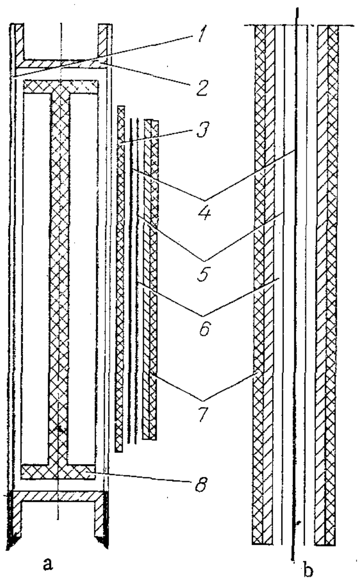

Fig. 1

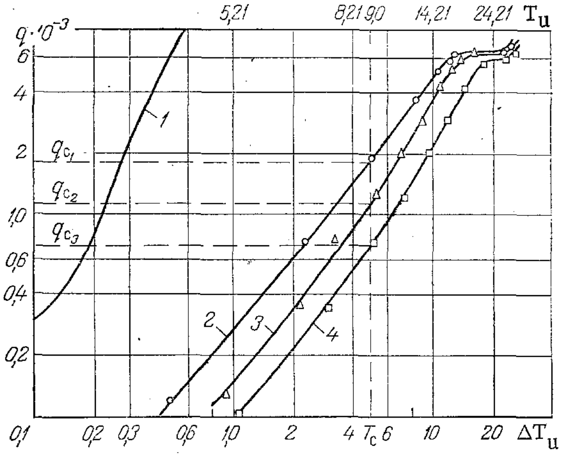

Fig. 2

Fig. 1. Experimental cell: membrane 1, bushing 2, Terylene film 3, heater 4, electrical insulation 5, thermocouple 6, substrate with coating 7, washer 8.

Fig. 2. Relation $q = f(\Delta T_u)$ during boiling of helium on copper-stabilized superconductor tapes (δ = 95 μm) with grade PETF-P-E coatings of various thicknesses (T_s = 4.21 K, active cell EE-1): 1) copper without coating [10]; 2) δ_c = 40 μm; 3) δ_c = 70 μm; 4) δ_c = 120 μm; q, W/m^2; ΔT_u, °K; T_u, °K.

The object of this study was to determine the dependence of the temperature of a vertical thin superconductor or copper substrate cooled by boiling helium in an open pool under atmospheric pressure on the material and the thickness of electrical insulation coatings. The results of this study have already been partially published [8, 9]. Here will be described the active elements of the device and will be reported experimental data on boiling of helium at each of the tested coatings.

The tests were performed with an apparatus consisting of a glass cryostat for helium with experimental cells (EE-1, EE-2) inside, a system of heat supply and regulation, and a temperature measuring system.

The experimental cell EE-1 (Fig. 1a) was a module with vacuum as thermal insulation, consisting of an annular bushing (2) 14 mm high and 80 mm in diameter with 50-μm-thick membranes made of stainless steel (1) soldered onto both sides. In order to stiffen the structure and prevent deflection of the membranes, a wavy Teflon washer (8) was inserted inside the bushing so as not to make contact with the part of the membrane holding the resistive heater. The inner cavity of this module was preevacuated to $\approx 10^{-2}$ mm Hg during its heating to 100°C, and then sealed. According to calculations, heat losses through the vacuum and along thermal bridges in the structure were thus reduced to a minimum and did not exceed 5% of the total heat load.

Onto the membrane, electrically insulated with Terylene (3), was cemented a 70 mm long and 8-10 mm wide heater (4) made of 18 μm thick Permalloy. The heater terminals, covered with grade POS-40 solder over a length of 10 mm, served as leads for the heating current. The heater surface was coated with an electrically insulating 5 μm-thick polyethylene film (5), through a layer of vacuum-grade lubricant.

Heat emitting 50-mm-long and 10-mm-wide specimens were placed on the heater segment heated by current, through a layer of vacuum-grade lubricant preventing leakage of helium under the heated plate.

As heat emitting surface with coating served a thin copper or copper-stabilized superconducting Nb_3Sn substrate (tape) with poorly heat conducting electrical insulation coating of various thicknesses on one side.

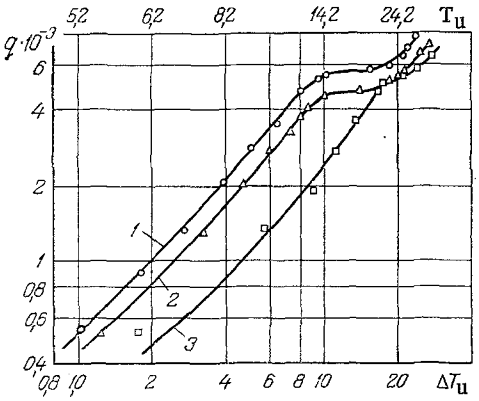

Fig. 3. Relation $q = f(\Delta T_u)$ during boiling of helium on copper substrates with grade PMF-352 coatings of various thicknesses (T_s = 4.2 K, active cell EE-2): 1) δ_m = 54 μm and δ_c = 43 μm; 2) δ_m = 152 μm and δ_c = 53 μm; 3) δ_m = 152 μm and δ_c = 115 μm.

Helium was made to boil on the coating. Onto the other side of the substrate, after it had been cleaned, was soldered the hot junction of a thermocouple (6).

The active cell EE-2 (Fig. 1b) was used, in addition, for some of the tests with helium boiling on substrates with poorly heat conducting coatings, this cell consisting of two vertical heat emitting plates 7 with equal areas and an electrically insulating film 5, a heater 4, and a thermocouple 6 placed between them. Each tested heat emitting plate was coated only on one side, viz. on the side of boiling helium. Such a design of a heat emitting conductor is most widely used in various kinds of superconductor devices.

Boiling was effected on plates with following coatings: a) film of grade PETF-P-E polyethyleneterephthlate (Terylene) with a polyethylene coating, δ_c = 15-120 μm, b) film of grade PMF-352 polyimide with Teflon coating, δ_c = 43-115 μm, c) grade PE-955 lacquer coating, δ_c = 10 μm.

The heat load was varied over the range from ≈100 W/m^2 up to the onset of film boiling.

The experimental data on boiling of helium on metal substrates with the given coatings are shown graphically in Figs. 2, 3 and in tabulated form. On the graphs along the upper axis of abscissas has been plotted the absolute temperature of the metal substrate under the coating and along the lower axis of abscissas has been plotted the temperature difference $\Delta T_u = T_u - T_s$ between that of the coating and that of liquid helium.

The tests have revealed that deposition of coatings and increasing their thickness results in much higher temperatures of the metal substrate under the coating. While the temperature of the uncoated metal surface under near-critical loads differs by ≈0.7°K from that of the boiling helium, accordingly, with relatively thin coatings (δ_c = 40-120 μm) deposited on the metal, the temperature of the latter will differ from that of the boiling liquid by already ≈10-18°K (Fig. 2). This means that at a relatively low specific thermal flux q_c (Fig. 2) the temperature of a superconductor with coating of a given thickness can rise up to the T_c point and, as a result, the conductor can pass from superconductor to normal state before the level q_{cr1} of crisis nucleate boiling has been reached. The temperature of the superconductor rises here due to the thermal resistance of the coating (ΔT_c) as well as due to the thermal resistance of the interface between heat emitting coating surface and liquid helium (ΔT_α), i.e., $\Delta T_u = \Delta T_c + \Delta T_\alpha$.

Reaching of the critical temperature T_c in the superconductor winding under operating conditions thus depends not only on the critical current I_c and on the critical magnetic field intensity B_c but also on the thermal resistance of the electrical insulation coating ($R_c \sim \delta_c/\lambda_c$) and the thermal resistance to heat emission ($R_\alpha \sim 1/\alpha$), the latter in turn depending on the hydrodynamic and operating parameters of helium: $T_c = f(I_c, B_c, R_c + R_\alpha)$, K.

Considering that to each combination of thermal resistances ($R_c + R_\alpha$) corresponds a certain limiting heat emission q_c in the superconductor at which the temperature of the latter reaches the T_c point, one can write $T_c = f(I_c, B_c, q_c)$, K.

TABLE 1. Values of q and ΔT_u during Boiling of Helium-1 on Coatings of Various Thicknesses, $\varphi = 90°$ and $P = 1 \cdot 10^5$ Pa

Coating grade															
PÉTF-P-É								PÉTF-P-É						PÉ-955	
experimental cell															
ÉÉ-2								ÉÉ-2						ÉÉ-1	
substrate material															
superconductor + copper								copper						copper	
coating thickness δ_c, μm															
15		40		70		120		20		40		70		10	
q	ΔT_u	q	ΔT_u	q	ΔT_u	q	ΔT_u	q	ΔT_u	q	ΔT_u	q	ΔT_u	q	ΔT_u
425	0,22	530	1,95	500	2,15	570	2,9	70	0,26	73,5	0,425	71	0,72	104	0,3
1230	0,54	1340	4,0	1400	5,6	1450	7,1	495	0,87	247	1,1	304	2,11	378	0,76
2300	1,02	2630	6,4	2700	8,6	2280	9,4	1320	1,79	525	1,97	828	4,31	312	1,14
3150	1,35	3600	7,9	3600	10,3	3000	12,5	1984	2,36	873	2,91	1418	6,05	1168	1,57
4100	1,8	4800	12,3	4600	11,7	3800	13,0	2709	2,97	1388	4,02	2602	8,58	1755	2,02
4500	2,2	5200	21,0	5200	15,0	4300	14,5	3528	3,64	1989	5,12	3550	10,5	2612	2,63
4800	2,65	6000	23,5	5500	23,0	4800	16,0	4226	4,38	2752	6,3	4548	12,5	3508	3,29
5000	16,0			6100	25,0	5300	19,2	4914	5,24	3602	7,56	4834	13,15	4148	3,72
5800	18,0					5600	21,0	4951	19,7	4510	9,05	5100	20,9	4340	3,9
6500	20,0					6200	22,5	5595	20,8	5215	11,1	5605	23,9	4572	17,9
										5340	21,1	6490	26,8	5312	20,2
										5520	22,0			6708	24,6

This equality indicates that overheating of a superconductor to the T_c point and its transition to the normal state can occur when the limiting heat emission q_c in the superconductor with electrical insulation coating has been reached at a current and a magnetic field intensity much lower than I_c and B_c respectively. This is a factor which must be taken into account in the design and construction of superconductor devices with electrical insulation coating on the conductors [11], inasmuch as "overheating" of such a conductor caused by the thermal insulation effect of the coating can not only degrade the electromagnetic characteristics of the device but also result in a fault transition of the superconductor to the normal state.

On the basis of the experimental data on the dependence of the temperature of copper-stabilized Nb_3Sn superconductor on the specific thermal flux emitted and on the thickness of the grade PÉTF-P-É poorly heat conducting coating (δ_c = 40, 70, 120 μm, Fig. 2), and taking into account the test data on boiling of helium at various saturation temperatures T_s (3.8-4.9 K) [12], the authors have arrived at an expression for the temperature of a metal substrate (superconductor + copper) under a coating

$$T_м = C\left(q\delta_c \frac{T_s}{T_{cr}}\right)^{1/3}, \text{ K}, \tag{1}$$

where $C = 23.7\ (m^{1/3} \cdot °K)/W^{1/3}$.

Expression (1) takes into account the effect of a temperature drop $\Delta T = T_W - T_S$, as a function of T_S and q, in accordance with the results of another study [12]. It is to be noted that the maximum error due to inaccurate determination of ΔT at various saturation temperatures T_S can be estimated as not exceeding ±5%. Expression (1) describes the experimental data of the study here (Fig. 2) with an error within ±30% over the ranges of parameters $100\ W/m^2 \leq q \leq q_{cr1}$ ($\approx 6000\ W/m^2$), $30 \leq \delta_c \leq 150$ μm, and $3.8 \leq T_S \leq 4.9$°K.

NOTATION

Here q (W/m^2) is the thermal flux density; q_c (W/m^2), threshold thermal flux density at which the superconductor temperature reaches the critical point; δ_c (m), thickness of the coating layer; T_u (K), substrate temperature underneath the coating; T_W (K), temperature above the heat emitting wall surface; T_S (K), temperature of saturated liquid; T_{cr} (K), critical temperature of the liquid; T_c (K), superconducting transition temperature; I_c (A/m^2), critical superconductor current density, B_c (Wb/m^2), critical magnetic field intensity; λ, thermal conductivity; and α is the heat transfer coefficient.

LITERATURE CITED

1. M. P. Malkov, I. B. Danilov, A. G. Zel'dovich, and A. B. Fradkov, Textbook on Physicotechnical Principles of Cryogenics [in Russian], Énergiya, Moscow (1973).
2. L. A. Novitskii and I. G. Kozhevnikov, Thermophysical Properties of Materials at Low Temperatures (Handbook) [in Russian], Mashinostroenie, Moscow (1975).
3. I. I. Perepechko, Low-Temperature Properties of Polymers [Russian translation], Khimiya, Moscow (1977).
4. A. P. Butler, G. B. James, B. I. Maddock, and W. T. Norris, "Improved pool-boiling heat transfer to helium from heated surfaces and its application to superconducting magnets," Int. J. Heat Mass Transfer, 13, No. 1, 105-115 (1970).
5. I. P. Vishnev, Ya. G. Vinokur, and V. V. Gorokhov, "Crisis nucleate boiling of helium at various surfaces," Inzh.-Fiz. Zh., 28, No. 2, 223-230 (1975).
6. D. N. Lyon, "Boiling heat transfer and peak nucleate boiling fluxes in saturated helium between λ-point and critical temperatures," Int. Adv. Cryogen. Eng., 10, 371-379 (1965).
7. V. A. Vasil'ev, Yu. P. Dmitrevskii, S. S. Kozub, and U. Ésher, "Temperature effects in superconducting pulse magnet," Preprint, Inst. Fiz. Vys. Energ., Serpukhov (1979).
8. I. P. Vishnev, A. I. Krauze, S. I. Sergeev, et al., "Studies of heat transfer and hydrodynamics in helium for cooling of superconductor devices," in: Reports to Scientific—Technical Conference on Equipment for Cryogenic Cooling of Superconducting and Cryoresistive Electrical Transmission Lines and Electrical Machinery with Superconductor Windings, Institute of Electrical Engineering, Slovak Academy of Sciences, Bratislava (Czechoslovakia), June 12-16 (1978), pp. 96-122.
9. I. P. Vishnev, Ya. G. Vinokur, O. A. Sedov, et al., "Study of certain problems pertaining to boiling of helium," in: Reports to Sixth All-Union Confer. on Heat Transfer and Hydraulic Drag during Flow of Two-Phase Stream through Components of Electrical Machines and Apparatus, Section I, Leningrad, September 24-26 (1978), pp. 75-77.
10. M. Jergel and R. Stevenson, "Static heat transfer to liquid helium in open pools and narrow channels," Int. J. Heat Mass Transfer, 14, No. 12, 2099-2107 (1972).
11. I. A. Glebov, I. P. Vishnev, V. G. Pron'ko, and I. A. Filatov, "Criterion of thermal stabilization in superconducting devices," Izv. Akad. Nauk SSSR, Energ. Transport, No. 4, 3-9 (1980).
12. I. P. Vishnev, Ya. G. Vinokur, and V. V. Gorokhov, "Boiling of helium under various pressures," Khim. Neft. Mashinostr., No. 9, 18-21 (1975).

PECULIARITIES OF CHILLING AN ARRAY OF PARALLEL CRYOGENIC PIPES

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The process of chilling parallel cryogenic pipes by a uniflow stream is analyzed with heat transfer between them taken into account.

Modern cryogenic power equipment often constitutes an array of parallel channels. Chilling of such equipment, i.e., dropping of its temperature from initial down to operating or some intermediate level is effected principally by means of a gaseous cryogenic coolant.

The object of this study is to determine the effect of heat transfer between pipes on the time taken to chill the equipment. The heat transfer can be effected in various modes: heat conduction through residual gases, radiation, and also heat passage through "thermal bridges." Thermal bridges in real structures are provided, for instance, by a dielectric layer between current-carrying components to be cooled, various electrically insulating spacers, etc.

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