THERMAL INSTABILITY AND TRANSIENT PROCESSES IN GAS-COOLED CURRENT LEADS

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The conditions under which burnup of gas-cooled galvanic current lead occurs are investigated theoretically and experimentally.

The current leads in modern superconducting systems operate, as a rule, under variable current loads and flow rates of the cooling gas. Fluctuations in the current and flow rate occur due to the characteristics of the superconducting system or due to breakdowns and can lead to burnup of the current lead. In this connection, there arises the need for determining the time over which the temperature of the current lead reaches the burnup temperature, and the relations between the current and the flow rate for which burnup of the current lead can occur (boundary of stability). These questions have been examined repeatedly in [1-7], but up to the present time the effect of important factors such as the intensity of cooling of the current-carrying part and its shunting by the superconductor on the stability boundary has not been adequately investigated. There are no experimentally confirmed dependences for calculation of the time at which the burnup temperature is attained.

In this work we performed theoretical and experimental investigation of the stability boundary using the real temperature dependences of the properties of the current-lead material and of the cooling agent and we obtained dependences for calculating nonstationary temperature profiles of the current lead.

The stability boundary was determined based on the solution of a system of equations describing stationary thermal processes in gas-cooled current leads:

$$\frac{d}{dx}\left(\lambda(T)S\frac{dT}{dx}\right)-\alpha(\Theta)F(T-\Theta)+\frac{I^2\rho(T)}{S}=0, \quad (1)$$

$$Mc_p\frac{d\Theta}{dx}-\alpha(\Theta)F(T-\Theta)=0. \quad (2)$$

The boundary conditions are:

$$T(0)=T_0,\ \Theta(0)=\Theta_0,\ T(l)=T_l. \quad (3)$$

As demonstrated in [8], it is useful to transform Eqs. (1) and (2) by introducing the variables $m = M/I$, $q = Q/I$, $\gamma = \alpha FS/I^2$, $\xi = xI/S$, $L = lI/S$ into the following form:

$$\frac{dT}{d\xi}=q/\lambda, \quad (4)$$

$$\frac{d\Theta}{d\xi}=\gamma(T-\Theta)/(mc_p), \quad (5)$$

$$\frac{dq}{d\xi}=\gamma(T-\Theta)-\rho. \quad (6)$$

In Eqs. (4)-(6), the complex ξ is the independent variable. Knowing the maximum value ξ_{max} that this complex can attain it is easy to calculate the limiting current of a given current lead. To calculate ξ_{max} we used the following condition: at the point of maximum temperatures $dT/d\xi|_{T=T_{max}}=0$. The calculation began from the cold end, at which the temperatures of the wall and of the gas are known, and proceeded up to T_{max}. The value of the

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heat inflow (target parameter) was selected so that at $T = T_{max}$, $dT/d\xi = 0$. Then, for this value of heat inflow, the calculation was performed up to T_l with $dT/d\xi|_{T=T_l} < 0$. The value of the independent variable ξ, obtained in this manner, is the value sought.

The algorithms developed permit calculating the stability boundary for arbitrary dependences of the parameters. However, within the framework of this work, we restricted ourselves to the following, in our opinion, practically important case: the current leads are prepared from the copper and the Nu number for the cooling gas is constant. The temperature dependences of the resisitivity and the thermal conductivity of copper were determined, as in [8], starting from the quantity ρ_{res}. The temperature dependence of the parameter γ with Nu = const is the same as the temperature dependence of the thermal conductivity of the cooling agent. The values of the parameter γ, presented in this work, were calculated at 5°K. The following conditions were used as the boundary conditions: $T_0 = \Theta_0 = 4.2$°K; $T_l = 300$°K. The calculations were performed on BÉSM-4M computer. The fourth-order Runge–Kutta method with the error monitor at each step was used. Stable solutions were obtained in the region of values of the parameters investigated: $0 \leqslant G \leqslant 5$ kg/(m•sec); $\rho_{res} = 10^{-10}$ Ω•m–10^{-8} Ω•m; $\gamma = \infty$; 10^{-12} W•m/(A^2•K) $\leqslant \gamma \leqslant 2 \cdot 10^{-9}$ W•m/(A^2•K); T_{max} = 300, 400, and 600°K.

In the investigation of the stability boundary, we examined current leads with a self-regulated flow rate and current leads with an independent flow rate. The current leads with the self-regulated flow rate are leads that are cooled by gas formed only due to the heat inflow along the current lead, while the current leads with the independent flow rate are leads for whose cooling the flow rate of gas is regulated and its magnitude is determined by the properties of the cryogenic setup. In the literature they are somethimes called refrigerated current leads. Some results of the calculations of the stability boundary for current leads with independent flow rate are shown in Fig. 1. This figure also shows the dependence (1), calculated for optimal, for each value of the flow rate, current leads. It is easy to verify that with a constant flow rate for cooling even a small excess above the optimum current can lead to burnup of the current-carrying part. The density of the current flowing along such a current lead can be increased only by increasing the flow rate of the cooling gas. With ideal cooling, due to the high gas flow rate, it is possible to pass a current with practically any magnitude along the current lead. With nonideal cooling this is impossible, and the behavior of the dependence $\xi(G)$ (curve 4 in Fig. 1) has a different form. Beginning with some value of the flow rate, the function $\xi(G)$ does not increase, i.e., there exists a limiting value of the current above which the burnup of the current lead occurs independent of the magnitude of the flow rate of the gas for cooling the current-carrying part.

To estimate the influence of the cooling intensity on the stability boundary, we performed calculations that showed that for $\gamma \geqslant 10^{-11}$–$5 \cdot 10^{-11}$ W•m/(A^2•K) the heat transfer in the curlead, in regards to burnup, may be assumed to be ideal. The indicated values of γ are much lower than the values of γ corresponding to ideal cooling ($\gamma \sim 10^{-8}$–10^{-9} W•m/(A^2•K) [8]) and determined starting from the heat inflow along the current lead. And, finally, as the calculation showed, the influence of shunting of the current-carrying part by the superconductor on the stability boundary is not unique. The stability boundary for shunted current leads (curve 5 in Fig. 1) expands compared to the nonshunted leads (curve 1) only for high flow rates of the cooling gas. The reason lies in the fact that as the flow rate increases the length of the superconducting section increases substantially and, therefore, liberation of heat in the current lead decreases.

The stability boundary was determined experimentally for current leads made of perforated tape (length 1 m, cross section $0.75 \cdot 10^{-4}$ m^2) and strand leads (1.1 m, $0.6 \cdot 10^{-4}$ m^2). The optimal current in the current leads made of the perforated tape is 1000 A, the minimum reduced heat inflow is 1.05 W/kA, and the residual resistivity is 10^{-9} Ω•m. For the strand current leads, these quantities equal, respectively, 1400 A, 1.5 W/kA and $2.7 \cdot 10^{-10}$ Ω•m. The intensity of cooling the perforated tape is close to ideal [8]: $\gamma = 1.35 \cdot 10^{-9}$ W•m/(A^2•K). The intensity of cooling of the strand leads is low [8]: $\gamma = 0.5 \cdot 10^{-10}$ W•m/(A^2•K). The minimum possible heat inflow along the current leads made of the same material as the stand current leads is ~1 W/kA. The current leads were externally thermally insulated by a layer of foam plastic ~60–100 mm thick. The current leads were placed into a standard helium cryostat with a volume of 60 liters. The variable flow rate of gas for cooling the current leads was produced by an evaporator placed in the liquid helium or by evacuation of gas from the cryostat, bypassing the current leads. Alternating current at the commercial frequency was fed into the current leads. The temperature of the surface was measured by copper–constantan thermocouples and was continuously recorded by an automatic plotting KSP-4 potentiometer. The temperature

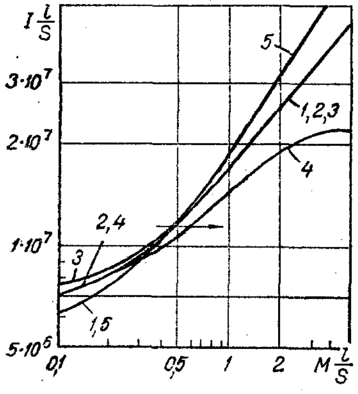

Fig. 1

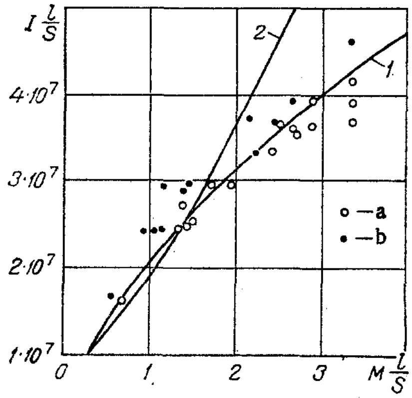

Fig. 2

Fig. 1. Stability boundary for copper current leads with residual resistivity of 10^{-9} Ω·m for different maximum attainable temperatures T_{max} and cooling intensities: 1 — $\gamma = \infty$, T_{max} = 300°K; 2 — ∞, 400°K; 3 — ∞, 600°K; 4 — $1.34 \cdot 10^{-11}$ W·m/(A²·K), 400°K; 5 — ∞, 300°K, the current lead is shunted by a superconductor with a critical temperature of 16°K. The arrow marks the reduced dimensions of thermodynamically optimum current leads. Il/S, A/m; Ml/S, kg/m·sec.

Fig. 2. Stability boundary of strand current leads: 1) calculation (real properties); 2) calculation (λ = const, $\rho = bT$); a) stable regime; b) unstable regime.

of the warm ring was maintained in the range 290 ± 20°K and that of the cold ring in the range 4.2–5°K. The experiments were performed in different order. In most of them, especially at high currents and flow rates of cooling gas, the gas was introduced first and then the current was established smoothly over a period of 10–15 sec. The temperature of the surface of the current lead was recorded with the current and flow rate maintained at a constant value. If the maximum temperature of the current lead exceeded 400°K, then the regime was viewed as being unstable and, vice versa, if the temperature was stabilized below 400°K, then the regime was assumed to be stable. In separate cases, the flow rate varied with an established current. As tests showed, the character of the regime did not depend on the order in which the current and flow rate were switched on. During the course of the experiments, no indications that the initial temperature distribution affected the character of the regime were observed. It should be noted, however, that this question was not investigated specially.

The results of the tests are presented in Fig. 2. This figure also shows the computed dependences, determined under the condition of ideal heat transfer. These dependences separate well the points corresponding to stable and unstable conditions. The coincidences of the computed (under the condition of ideal heat transfer) stability boundary and the experimentally determined boundary confirms the theoretical conclusion that the intensity of cooling has virtually no effect on the stability boundary.

The maximum value of the current fed along the current leads was 2800 A. The current densities attained along the perforated tape and strand current leads equal $3.5 \cdot 10^7$ A/m² and $4.18 \cdot 10^7$ A/m², respectively. The computational procedure developed also permitted determining the stability boundary of current leads with the self-regulated flow rate (Fig. 3). They can operate stably for currents only insignificantly above the optimum value. This is explained by the fact that an increase in the temperature of the current lead on a section close to the warm end has virtually no effect on the axial heat inflow to the liquid helium and practically does not increase the flow rate of the cooling gas. Thus, for example, for copper current leads with a residual resistivity of 10^{-9} Ω·m the heat inflows along the optimal current leads and current leads with a maximum temperature of 600°K constitute 0.99 and 1.03 W/kA, respectively.

Shunting of the current leads by the superconductor with the self-regulated flow rate does not extend their stability boundary.

The solution of the stationary problem permitted establishing the conditions for stable operation of current leads with a current of constant magnitude and for constant flow rate of the cooling gas. For short-time current excesses accompanying drops in the flow rate, the

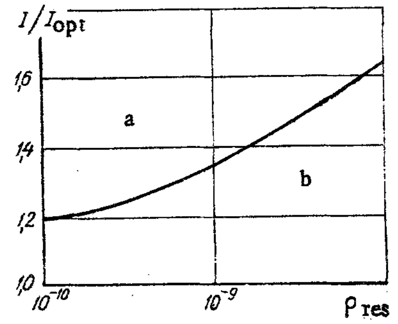

Fig. 3

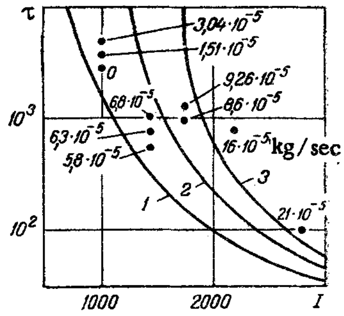

Fig. 4

Fig. 3. Stability boundary of current leads with the self-regulated flow rate: a) unstable region; b) stable region. ρ, Ω•m.

Fig. 4. Dependence of the time for attaining a temperature equal to 350°K in strand current leads at the point with a coordinate of 1.06 m on the current: 1) $M = 10^{-5}$ kg/sec; 2) $5 \cdot 10^{-5}$; 3) 10^{-4} kg/sec, τ, sec; I, A.

condition for stable operation must be determined from the solution of the nonstationary problem, which can be formulated as follows. One or both parameters change in the current lead with a fixed flow rate of cooling gas and current. It is necessary to determine the temperature profile along current lead at each time after the change in the regime parameters and the time at which the maximum temperature of the current lead attains the burnup temperature.

The system of differential equations, describing the thermal processes occurring in the gas-cooled current lead, have the form

$$c_{\text{M}}\rho_{\text{M}} S \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda S \frac{\partial T}{\partial x}\right) - \alpha F (T - \Theta) + I^2\rho/S, \tag{7}$$

$$Mc_p \frac{\partial \Theta}{\partial x} = \alpha F (T - \Theta) \tag{8}$$

with the boundary conditions

$$T(0,\ \tau) = T_0,\ T(l,\ \tau) = T_l,\ \Theta(0,\ \tau) = \Theta_0. \tag{9}$$

As an initial condition we can choose the temperature distribution corresponding to thermodynamically optimal conditions [5]:

$$T(x,\ 0) = T_0 \exp\left(\frac{x}{l} \ln \frac{T_l}{T_0}\right). \tag{10}$$

To obtain the quantitative characteristics of the transient process, we shall find an analytic expression for the problem formulated under the following assumptions: the thermal conductivity and heat capacity of the current lead material and of the cooling gas are constant, heat transfer in the current lead is ideal, and the resistivity is a linear function of temperature: $\rho = \rho_{\text{res}} + b(T - T_0)$.

Under these assumptions, the system of equations (7) and (8) reduces to the form

$$c_{\text{M}}\rho_{\text{M}} S \frac{\partial T}{\partial \tau} = \lambda S \frac{\partial^2 T}{\partial x^2} - Mc_p \frac{\partial T}{\partial x} + [\rho_{\text{res}} + b(T - T_0)]\, I^2/S. \tag{11}$$

Equation (11) with the conditions (9) and (10) is the general first problem of heat conduction. The solution of (11), obtained by the method of separation of variables, has the form

$$T(x,\ \tau) = \frac{\exp(\mu x)}{b}\left\{\sum_{n=1}^{\infty}\left[(C_n + D_n)\exp\left\{\left[h - \left(\frac{\pi n}{l}\right)^2 a^2\right]\tau\right\} - D_n\right] \times \right. \tag{12}$$

$$\left. \times \sin\frac{\pi n}{l} x + \rho_{\text{res}} + \frac{x}{l}\left[\frac{\rho_{\text{res}} + b(T_l - T_0)}{\exp(\mu l)} - \rho_{\text{res}}\right]\right\} + T_0 - \frac{\rho_{\text{res}}}{b},$$

where

$$\mu = \frac{Mc_p}{2\lambda S};\quad h = \left(I^2 b - \frac{M^2 c_p^2}{4\lambda}\right)\frac{1}{c_M \rho_M S^2};\quad a^2 = \frac{\lambda}{\rho_M c_M};$$

$$D_n = \frac{2h}{\pi n\left[\left(\frac{\pi n}{l}\right)^2 a^2 - h\right]}\left[\frac{\rho_{res} + b(T_l - T_0)}{\exp(\mu l)}(-1)^n - \rho_{res}\right];$$

$$C_n = C_{n1} + C_{n2} + C_{n3};\; C_{n1} = \frac{2(\rho_{res} - bT_0)}{\left[\left(\frac{\mu l}{\pi n}\right)^2 + 1\right]\pi n}\left[1 - (-1)^n \exp(-\mu l)\right];$$

$$C_{n2} = \frac{2bT_0}{\pi n\left\{1 + \left[\left(\frac{1}{l}\ln\frac{T_l}{T_0} - \mu\right)\frac{l}{\pi n}\right]^2\right\}}\left[1 - (-1)^n \exp\left(\ln\frac{T_l}{T_0} - \mu l\right)\right];$$

$$c_{n3} = \frac{2\left[\rho_{res} + b(T_l - T_0)\right]}{\pi n \exp(\mu l)}(-1)^n - \frac{2\rho_{res}}{\pi n}.$$

The solution (12) shows how the temparture profile of the current lead with the current and flow rate established at the time $\tau = 0$ will change. The nature of the change in the temperature profile with time is determined by the sign of the exponent $H = h - \left(\frac{\pi}{l}\right)^2 a^2$ in front of τ. A stationary temperature distribution is established along the current lead for $H < 0$, while for $H > 0$ the temperature of the current lead will increase indefinitely. The stability boundary corresponds to the value $H = 0$. The relation between the current and the flow rate at the stability boundary has the form

$$I\frac{l}{S} = \sqrt{\left(\pi^2\lambda + \frac{M^2 c_p^2}{4\lambda}\right)\frac{1}{b}}. \tag{13}$$

As expected, the stability boundary, determined form the solution (12), completely coincides with the stability boundary obtained in [1] from the condition of singularity of the solution of the stationary equation. The solution of the equation shows that the reason for the indefinite growth in the temperature of the current lead for currents exceeding the critical value is the resistivity of the material of the current lead which increases with temperature. In a current lead prepared form a material with ρ = const, a stationary temperature profile must always theoretically be established. However, it does not follow from this that such a current lead will not burn up, since the maximum value of the temperature of the current lead is not bounded and for sufficiently high currents it can exceed the melting temperature of the current-carrying part.

The main purpose of solving (11) was to obtain a dependence for calculating the time for attaining the burnup temperature with transient processes. Direct use of (12) can lead to large errors, since the real stability boundary and the stability boundary determined from (13) do not coincide. An analysis showed that the main reason for the disagreement is the inadequate accuracy with which the liberation of heat is taken into account in the model adopted in solving the nonstationary equation. In this connection, it was proposed that a more accurate value be found for the amount of heat liberated using in (12) instead of the mean integral value of the temperature coefficient of the resistivity, its effective value (b_{ef}). It (b_{ef}) was chosen so that for values of the current and flow rate corresponding to the real stability boundary, the value of H would equal 0. An experimental check was made for strand current leads and perforated tape leads. The results are presented in the form of dependences of the time at which the burnup temperature is achieved on the current (Fig. 4). Comparison of the computed and experimental data show that the disagreement between them does not exceed 50%.

NOTATION

x, coordinate along the current lead; τ, time; T, Θ, temperature of the current lead and of the cooling gas; Q, heat inflow; T_{max}, maximum attainable temperature of the current lead; S, l, F, cross section, length, and cooling parameter of the current-carrying parts; ρ, λ,

c_m, ρ_m, b, resistivity, thermal conductivity, heat capacity, density, and temperature coefficient of the resistivity; I, current; M, c_p, flow rate and heat capacity of the cooling gas; α, heat-transfer coefficient. The indices are: 0, l correspond to quantities referring to the cold and warm ends of the current lead; res indicates residual, and ef indicates effective.

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GETTERING EFFICIENCY DURING MASS TRANSFER IN A VACUUM

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The results of an investigation of the composition of the residual atmosphere in an "open" vacuum and inside a quasiclosed volume during electron-beam vaporization of molybdenum and niobium are presented.

The comparison of the efficiencies of gettering gas particles caused by the vaporization of a substance in an "open" vacuum and inside a quasiclosed volume located in a vacuum [1] is of great practical interest. Here it is important to note the presence of two simultaneously occurring processes of mass transfer: the transfer of the substance being vaporized and the transfer of the residual atmospheric gas.

The experiments were carried out on a vacuum installation, from the working chamber of which air was evacuated by a VN-2 roughing pump and a VA-2-3 diffusion pump in series. The working chamber of the vacuum installation, made of stainless steel, consisted of a hollow cube 600 mm on a side with a wall thickness of 10 mm. The chamber was equipped with a U-530M electron-beam gun operating jointly with a U-250A apparatus. The vauum was measured with standard PMT-2 and PMI-2 gauges connected to a VIT-1 vacuum meter. The partial pressures of the residual gases were determined on an APDM-1 monopolar mass spectometer with an MMS-2A sensor. The quasiclosed volume, made of niobium or molybdenum foil 0.5 mm thick, consisted of a cylinder 100 mm in diameter and 350 mm long. This cylinder and the MMS-2A sensor were fastened to an interchangeable flange so that the target being vaporized was on the opposite

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