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Temperature rise of copper and HTSC tapes in liquid nitrogen by a step-wise current pulse

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Abstract

Features of a heat transfer to liquid nitrogen from copper or superconducting tapes loaded by a short step-like current pulse have been studied experimentally. The delay of a heat transfer development have been observed and studied. A phenomenological model enabling us to describe qualitatively the non-stationary heat transfer process on the basis of the stationary boiling curve is proposed.

Keywords: Heating development, high-temperature superconductors, overload conditions, pulse measurements, thermal factors

1. Introduction

Recent advances in the technology of high temperature superconducting (HTS) materials intensified the HTS electrical equipment development. Transient electrical and thermal processes are of great importance in the operation of many types of this equipment. The transient processes are especially essential in the case of the resistive fault current limiters. The transition of their superconducting element to the normal state is accompanied by a sharp increase of the Joule heat dissipation. The fault current mode lasts usually a few tens of milliseconds, therefore, a study of the characteristics of a transient heat transfer to liquid nitrogen is required. Previously, to evaluate the temperature rise of the HTS tape an adiabatic approach has been assumed [1, 2]. According to [3], an account of heat transfer to liquid nitrogen by thermal conductivity is essential. Recently, an attention was called to a delay time of nucleate boiling heat transfer (an onset of bubble nucleation on the tape surface) [4, 5, 6, 7, 8].

Our paper deals with a study of the transient thermal processes in copper and HTS tapes immersed in liquid nitrogen loaded by single step-wise current pulses with different height and duration. The temporal dependence of voltage drop between the terminal taps for copper and stabilized HTS tape SCS4050 is measured. A phenomenological model is proposed to evaluate the time delay to onset the nucleate boiling of nitrogen.

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2. Method and measurement results

An experimental setup was designed to measure the temporal dependence of the voltage drop between the terminal taps for copper and HTS tapes immersed in liquid nitrogen and loaded by a single step-wise current pulses at given value of the current step. It allows us to study the thermal process of the tape at a step-wise current pulses up to 500 A in amplitudes.

The cross-section dimensions for copper tape and for a stabilized 2G HTS SCS4050 tape were the same (w = 4 mm in width and δ = 0.1 mm in thickness). Figure 1 shows the temporal dependence of the temperature excess ΔT of a copper tape over the saturation temperature of liquid nitrogen for different values of current I in the range from 124 A up to 202 A. The tape temperature is clearly seen to change with time non-monotonically. It increases rapidly at the beginning of transient process, reaches the peak value at instant $t = t_{\max}$ and then decreases making a close approach to the steady-state value which depends on the given current value (see inset in Fig. 1). The observed behavior of the $\Delta T(t)$ versus t is related to the activation process of the nucleation cites.

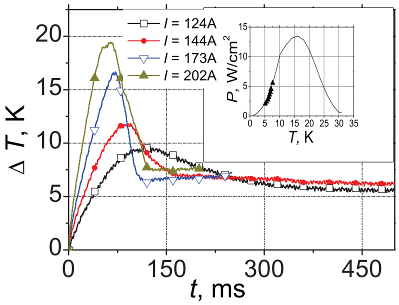

Fig. 1. Temporal dependence of the temperature excess for copper tape at different values of a current step shown in the legend. The steady-state boiling curve of liquid nitrogen is presented in the inset by solid line. Our experimental data are shown by solid points.

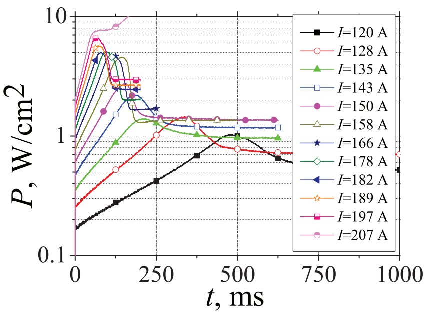

Fig. 2. Temporal dependence of the HTS tape dissipation for current pulse amplitudes shown in the legend.

Contrary to the data in Fig. 1, results in Fig. 2 for 2G HTS tapes show the power dissipation P along the ordinate axis but not the overheat temperature. The point is that the tape remained in the superconducting state. (Note that at a current I = 207 A the transition to a steady-state nucleate boiling does not occur. We see a continuous heating of the tape). Accordingly, we could not determine the temperature of the HTS tape directly, since the base characteristics, namely the temperature dependence of resistivity is related to the normal metal state only. Therefore, to estimate the surface temperature of the HTS tape, we use the results of Ref. [3] where it was shown that before the nucleate boiling onset at about 50% of the dissipated energy was transferred to liquid nitrogen by the thermal conduction. According to this estimation, the tape overheat did not exceed 13 K.

The measurement results of the nucleate boiling activation time $\tau = t_{\max}$ versus dissipation heat flux P for copper and HTS tapes SCS4050 are shown in Fig. 3. The time delay is seen to be higher for HTS tape than for the copper one. For further action it is convenient to replot the data shown in Fig. 3 in other variables (see Fig. 4). Let the dimensionless dissipation parameter $\beta = P/P_b$ be along the x-axis where P is a heat flux, P_b = 0.64 W/cm^2 is the heat flux corresponding to the transition of nitrogen to the nucleate boiling on the both tape surface in the steady-state regime. The relation of the t_{max} to the linear heat capacity C_l at T = 77 K of the tape $\tau = t_{max}/C_l$ is determined along the ordinate axis.

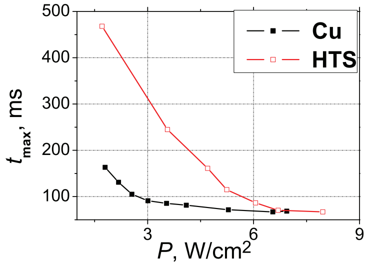

Fig. 3. The activation time t_{max} of nucleate boiling *vs.* heat flux P for the copper and HTS tapes.

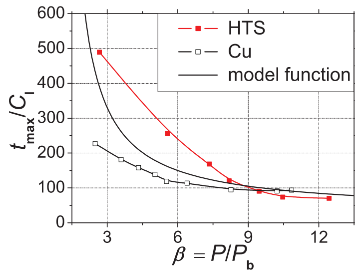

Fig. 4. The reduced activation time $\tau = t_{max}/C_l$ of nucleate boiling *vs.* heat flux P for the copper and HTS tapes. A black curve without symbols is a model function $f(\beta)$.

3. Discussions

Consider the equation of transient heat balance for the tape:

$$\frac{d}{dt}C(T)T(t) + 2(w + \delta) \cdot l \cdot q(T) = \mathcal{P}(T, t), \tag{1}$$

where l is the tape length, $C(T)$ is the heat capacity of the tape, $\mathcal{P}(T, t)$ is the Joule dissipation, and $q(T)$ is a heat flux transferred to liquid nitrogen. The function $q(T)$ characterizing the steady-state boiling curve of liquid nitrogen [9] can be used to describe the stationary processes only whereas we operate in the transient regimes. To take this fact into account, we replaced the function $q(T)$ by $q(T, t)$ (see Eq. (2)) introducing two additional temporal parameters τ_1 and τ_2. The first parameter τ_1 is the delay time of the onset of the natural convection,the second parameter τ_2 is the delay of the onset of the nucleate boiling.

$$q(T, t) = 10^{-4} \times \begin{cases} 0 & t \le \tau_1 \\ 10^{3.2105} \cdot (T - 77.3) & \tau_1 < t \le \tau_2\,; \\ 10^{2.8681} \cdot (T - 77.3)^{2.1748} & t > \tau_2 \end{cases} \tag{2}$$

Since the delay τ_1 is a small value which is about 3 ms, the process at $t < \tau_1$ can be considered as adiabatic. The observed difference in the delay for the copper and HTS tapes is unexpected because it seems that the delay τ_2 is mainly determined by the properties of liquid nitrogen. The physical reason of the discussed difference may be connected with the non-uniform heating of the HTS tape owing to its non-uniform structure. To avoid this difficulties and evaluate the delay τ_2, we introduce an empirical function $f(\beta)$ which is shown in Fig. 4. This function is presented by a mean line between two experimental curves in the same figure. In general case this function and the delay τ_2 can be evaluated by means of Eq. (3)

$$f(\beta) \approx 30 + 600/(\beta - 1), \qquad \tau_2 \approx f(\beta) \times C_l, \qquad \tau_2 \quad \text{in} \quad \text{ms}. \tag{3}$$

A comparison of our experimental data with calculation results using the proposed model is shown in Fig. 5. For these evaluations we used the tape SCS4050 with linear heat capacity $C_l = 0.96$ J/m K. One can see a rather good agreement between the measurement data and the model predictions.

Our model coincides with the experimental results presented in recently published paper [10] too. So, according to the data presented in Fig. 6 from [10], τ_2 for 2G HTS taped is about 0.64 s for pulse current amplitude $I = 140$ A and about 1 s for $I = 130$ A, whereas our model gives 0.6 s and 0.88 s, accordingly. Moreover, our model gives good results with respect to 1G tapes also. Results of a comparison of the experimental data from [10] with our model prediction are shown in Fig. 7 where the lines with symbols represent the experimental data of the temporal dependence of the voltage drop across a sample of 1G HTS tapes obtained in [10] (see, the right ordinate axis). The lines without symbols demonstrate the calculation data

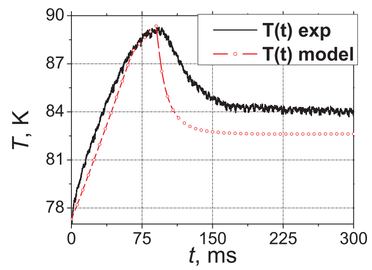

Fig. 5. A comparison of the experimental and calculation results performed within the empirical model for copper tape and current I = 144 A.

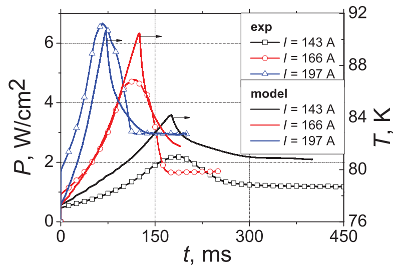

Fig. 6. A comparison of the experimental and calculation results performed within the empirical model for the superconducting tape.

which obtained by means of our phenomenological model for the same current values as in the experiment. The experimental and model peak positions are clearly seen to agree well. One can see a good agreement between the model prediction and experimental data for the delay τ_2.

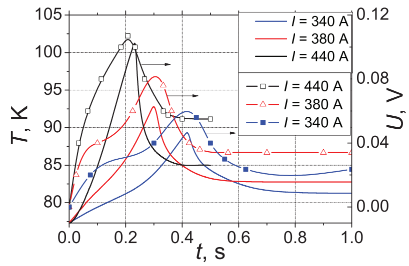

Fig. 7. A comparison of the experimental data for the 1G superconducting tapes from [10] with calculation results performed using our empirical model.

4. Conclusion

Thus, we have studied experimentally the features of temporal temperature variation of copper and HTS tapes in liquid nitrogen caused by the step-wise current pulse advancing. We have determined the nucleate boiling activation time to occur the nucleate boiling heat transfer mode of liquid nitrogen on the tape surface. We have developed also a empirical model to predict the transient temperature variation of copper and HTS tapes in liquid nitrogen caused by the step-wise current pulse advancing. Its predictions correlate rather good with the experimental data of this paper and data of [10]. The obtained results can be used to design and construct the HTS fault current limiters and other electric devices and equipment.

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