Analysis of behaviour of HTS tapes cooled by liquid nitrogen under currents more than the critical current

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Abstract. For proper HTS device protection knowledge is necessary about the behaviour of HTS tapes cooled by liquid nitrogen at current pulses more than critical current. In our previous works, we performed measurements of HTS tapes at the currents more than critical currents and found the peculiarities on voltage – current characteristics of HTS tapes. Later, the coupled thermal and electric numerical model was developed to analyse the behaviour of the HTS tape in these conditions. The numerical model helped us to understand qualitatively the heat transfer from the HTS tapes to liquid nitrogen. The peculiarities found were connected not only with the nonlinearity of electrical conductivity of the superconductors but with boiling hysteresis phenomenon in the liquid nitrogen as well. In the present paper we made additional suggestions about peculiarities in the nuclear boiling heat transfer. We also described the way to find out the real heat transfer coefficients during convection and nucleate boiling in liquid nitrogen by using data from measurements of voltage – time characteristics of the HTS tape cooled by liquid nitrogen at current pulses more than critical current.

1. Introduction
Specific behavior of HTS tapes cooled by the liquid nitrogen at current pulses more than their critical current (at overload currents) observed in [1] were associated not only with nonlinear electrical conductivity of the superconductor but also with the nuclear boiling (NB) hysteresis phenomenon in the liquid nitrogen. For fluids with the hysteresis like the liquid nitrogen it is possible to investigate the hysteresis phenomenon if the boiling curves will be obtained at the increasing and decreasing of the heat flux. Many researchers studied NB hysteresis by this method, for example in [2-4]. For the HTS tapes one can get the increasing of the heat flux during superconducting to normal-conducting current transition at overload currents. On the other hand, the decreasing heat flux happens during transition from normal to superconducting part [1]. We continue to study the peculiarities of boiling heat transfer to liquid nitrogen with use of the coupled thermal and electric numerical model that allowed us to calculate behavior of the HTS tapes at overload currents.

2. Measurements

2.1. Experimental arrangements
General experimental arrangements and the details of experiments were the same as described in [5]. HTS tapes were tested in an open liquid nitrogen bath-type cryostat using the programmed DC power supply and the multichannel data acquisition system. In these experiments five thermocouples (TC) were...
attached to each sample with distance 1 cm between them. One pair of the voltage taps was attached with the distance 10 cm between them. Thus, all thermocouples were between the voltage taps. During tests the current pulse was applied to the sample with the certain current magnitude and duration. The current, voltage and TC signals were recorded by the multichannel Yokogawa™ DL850 analysing recorder. Measurements were made for horizontal - “flat” and vertical - “edge” orientation of the tapes (Fig.1) in the cryostat.

2.2. HTS tape
We used Sumitomo BSCCO tapes (DI-BSCCO™) type HT (Reinforced Copper Alloy) because 1G tape has large thermal quench current (below this current HTS conductor can operate stable) [1]. The critical current ($I_c$) determined by $1 \mu V/cm$ criteria and the $n$-value were important to analyse tapes behaviour at overload currents. Our measurements of $I_c$ and $n$-values of the tape are shown in Fig. 2.

![Image](image1.png)

**Figure 1.** “flat” and “edge” of tapes’ orientation in the cryostat.

![Image](image2.png)

**Figure 2.** Critical currents and $n$-values of the HTS tape versus temperature.

3. Experimental results
Several voltage-time recordings are shown in Fig.3 at different currents and orientations of tapes. The currents applied are more than the critical current but lower than the thermal quench current. For voltage and temperature time recordings currents were applied to samples as it is shown in Fig. 4. One can see that the orientation of the tapes has weak influence on the samples behaviour. It was found that the thermal quench current of the tape in the liquid nitrogen is about 460 A and does not depend on the orientation of tapes also.

![Image](image3.png)

**Figure 3.** Voltage recordings versus time for tests at different currents.

![Image](image4.png)

**Figure 4.** Currents in the HTS tapes versus time.

In Fig. 5 several temperature differences $\Delta T$ are shown between the tape temperature and the liquid nitrogen temperature. The results are presented for one thermocouple for each of the orientation of the tape.
Figure 5. Measured temperature difference versus time curves at different currents.

4. Simulation Model

4.1. Numerical model

The coupled numerical transient electric-thermal model was developed to obtain the characteristics of the HTS tape and the liquid nitrogen at overload currents. The details of the model are described in [1]. In the electric part of the numerical model the transition characteristic of the HTS tape is assumed as:

$$E = E_c \left( \frac{I}{I_c(T)} \right)^{n(T)}$$

where $E_c = 1 \mu \text{V/cm}$, $I_c(T)$ and $n(T)$ of the tape presented in Fig. 2.

4.2. Model of Heat transfer to nitrogen

In the thermal part of the numerical model, the major problem is the proper modeling of the heat transfer to liquid nitrogen with taking into account the hysteresis phenomenon. The hysteresis means a delay of the onset of NB when the heat flux increases, but no discontinuity when the heat flux decreases. The overheating (overshoot) of temperature difference $\Delta T_{oh}$ prior to start of NB can be much more than the temperature difference ($\Delta T_{bc}$) during switching back from NB to natural convection. Using the model of the hysteresis described in [1], it was possible to explain the behavior of the voltage in the tape at current overloads qualitatively. In that model, we assumed that the transition from natural convection occurs immediately to fully developed NB.

In this work we made additional suggestions about peculiarities in the NB heat transfer. Namely, that the hysteresis may strongly depends on the conditions of an experiment [2], and that the hysteresis may occur during both the boiling incipience and the boiling development [4]. In our reasoning, we assume that the hysteresis depends on the magnitude of overload currents. It also means, that the heat flux density to the liquid nitrogen is depending on the current ramp rate. We assumed that the transition from the convection initially occurs to partially developed NB. The general characteristics of the boiling curves for two cases are shown in Fig. 6: if there is transition first from the convection to partially developed NB and then to fully developed NB and if there is transition from the convection straight to fully developed NB. The temperature differences shown in Fig. 6 are: $\Delta T_{b,c} -$ temperature difference of switching back from NB to the convection, $\Delta T_{c,pb} - \Delta T_{bc}$ prior to incipient of partial developed NB, $\Delta T_{c,pb} - \Delta T_{oh}$ prior to incipient of fully developed NB. It is always $\Delta T_{c,pb} < \Delta T_{bc}$. In the case of transition to partially developed NB, there are a number of boiling curves located between the points ABC shown in Fig. 6 depending on $\Delta T_{c,pb}$. We consider that the maximal measured temperature difference presented in Fig. 5 is just the $\Delta T_{c,pb}$ for the corresponding overload current. The measured overheating temperature difference $\Delta T_{c,pb}$ versus the currents for the tape are shown in Fig. 7. The typical results are presented for two thermocouples for each the orientation of the tape. Other thermocouples demonstrated similar behavior.

Peculiarities of the hysteresis were taken into account in the thermal part of our numerical model.
For the natural convection the known relationship for Nusselt number [6] can be transformed to equations for heat transfer coefficient:
\[
\alpha_{\text{conv}} = C_{\text{conv}} \cdot \Delta T^{m_1}
\]  
(2)

where \(C_{\text{conv}}\) coefficient depends on the size of the sample, \(m_1=1/4\) or \(1/3\) depending on Rayleigh number. For the NB regime the heat transfer coefficient depends on the heat flux as follows:
\[
\alpha_b = C_b \cdot q^m
\]  
(3)

Where the coefficient \(C_b\) and \(m\) depend on heater surface/fluid characteristics and ramp rate of heat flux density \(q\). For fully developed NB for copper/nitrogen \(C_b = 12\), and \(m = 0.624\) [3]. We assumed the different values of \(\Delta T_{c_pb}\) to be accounted for a different partial NB regime.

4.3. Simulation results

As mentioned above to analyse the behavior of the voltage in the tape we used overheating temperature difference \(\Delta T_{c_pb}\) presented in Fig. 7. In Fig. 8 the calculated and measured voltages versus time for the tape are shown. In calculations the currents in the HTS tape are the same with measured shown in Fig. 4. The calculated and measured voltages for the HTS tapes are well coincided. \(\Delta T_{c_pb}\) and the coefficients \(C_b\) and \(m\) for the corresponding overload currents used in the calculations are shown in the Table 1. For partial developed NB coefficient \(C_b\) is less then \(C_b\) for fully developed NB, coefficient \(m\) is more for partial developed NB then \(m\) for fully developed NB.

Fig. 9 presents the calculated curves of NB hysteresis in form of the heat transfer coefficient versus the heat flux for different overload currents. One can see in the Figure 9 that the heat transfer coefficient on lower and upper hysteresis curves can differ by two orders of magnitude. For example, Fig. 10 presents the calculated heat transfer coefficient versus time for different overload currents.
Table 1. Parameters for simulating of the nitrogen NB.

| Current, A | $\Delta T_{c,b}$ | $C_b$ | $m$  |
|-----------|-----------------|------|------|
| 326       | 5               | 2    | 0.8  |
| 363       | 6               | 3.5  | 0.76 |
| 382       | 7               | 6    | 0.75 |
| 419       | 8               | 8    | 0.72 |
| 437       | 8.5             | 10   | 0.68 |
| 456       | 9               | 12   | 0.65 |

Figure 9. Calculated the heat transfer coefficient dependence on the heat flux from HTS tape.

Figure 10. Calculated the heat transfer coefficient versus time.

5. Conclusions

The numerical model has been developed to analyse the behaviour of the HTS tapes cooled by liquid nitrogen at overload currents. The numerical analysis demonstrated that there is the hysteresis phenomenon in the boiling nitrogen during heat transfer process from overloaded HTS tapes to the nitrogen. The hysteresis phenomenon depends on the magnitude of overload currents. The suggested model of the hysteresis phenomenon provided numerical results practically coincides (see Fig.8) with the experimental results and can be used for evaluation of the HTS tapes behaviour at overload currents. Characteristic parameters were determined experimentally to describe the boiling hysteresis phenomenon and the estimation of the heat transfer coefficients that corresponds to the nucleate boiling.

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7. References

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