The influence of cooling on the magnetic properties of the second generation HTS tapes

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Abstract. In this work it is presented a computational model of a magnetic system based on stacks of high-temperature second generation superconducting tapes (HTS) GdBa2Cu3O7-x. The model is designed to calculate magnetic systems based on HTSC tapes taking into account the thermal processes occurring in the layered structure of the tape. The dependences of the trapped magnetic flux and the cooling power on the temperature for different magnetization durations were obtained, and the dynamics of thermal processes taking in the tape during magnetization was analyzed.

1. Introduction
Currently, HTS tapes are used extensively in the manufacture of trapped flux magnets, HTS bearings, levitation suspensions and other levitation devices. The magnetic properties and levitation characteristics of the tapes stacks depend not only on critical characteristics of the used materials but its geometry, conditions of magnetization and cooling. The local heat jumps in the superconducting material can contribute the transition between superconducting state and normal state, complete degradation of the trapped magnetic flux, and, as a consequence, the failure of the working device. Therefore, it is necessary to predict the behavior of high-temperature superconducting tapes in an external magnetic field, taking into account the thermal processes occurring within their layered structure. The present work is devoted to the development of a numerical model that makes it possible to calculate the parameters of a magnetic system based on HTS tapes taking into account heating processes in the system.

2. Computational model
The measurements were performed on a superconducting tapes produced by SuperOx (Russia) with the width of 12mm, thickness of the superconducting layer GdBa2Cu3O7-x is 1 micron and the critical current - 300 A (criterion 1 μV / cm, 77 K, own field). The simulated system is a layered structure of the superconducting tape containing a substrate, a superconducting layer, and also a stabilizing layer of copper. By the others layers we neglect because of their small thickness and small influence on the thermal processes. Cooling within the model is carried out by a cupper bulk, which is a cryocooler analog. The outer boundary of the cryocooler, which is in direct contact with the HTS tape substrate, is set as a cooling source with a determined constant temperature. In the study, we calculated the power, corresponding to the real cooling system power, which is necessary to hold the set temperature in the system. The sample is in a vacuum. The tape is placed on a cupper bulk that will be considered as a cooling source. An external uniform magnetic field, 2T of magnitude, linearly...
increases and then similarly linearly remove out of the system. The geometry of the system is shown in the Figure 1.

![Figure 1. The geometry of the magnetic levitation system.](image)

To describe the superconducting magnetic system we used Faraday and Ampere laws equations. The resistance nonlinear dependence on the current is given by the power law (1) and the current-voltage characteristic can be written by formula (2):

\[ \rho = \frac{E_c}{J_c} \left( \frac{|I|}{J_c} \right)^{n-1} \]  

\[ E = \rho \cdot J \quad (2) \]

where \( E_c \) is the electric field which equals 1 \( \mu \)V/cm, that corresponds to the critical current. The \( n \)-value is assumed to be 21, which is typical for the samples of HTS tapes. The critical current density \( J_c \) is determined on the basis of the transport measurements of the used HTS tapes.

The model was developed on the base of the finite element method, which was implemented using the Partial Differential Equations (PDE) form of the Comsol Multiphysics software module. In Comsol Multiphysics the general PDE standard equation view is (3):

\[ e_a \frac{\partial^2 u}{\partial t^2} + d_a \frac{\partial u}{\partial t} + \nabla \times \Gamma = F \]  

Here the dependent variable, magnetic field \( u = H(x,y,z) \), is chosen in the entire space. The parameters of equation (3) are chosen in such a way that equation becomes Faraday's law. Specifications of the parameters of the equations (3) see [1].

Also, in this model it is taken into account the dependence of the critical current on the magnetic field perpendicular to the wide surface of the tapes [2] and experimental dependence of the critical current on the temperature, that described by formula (4):

\[ I_{c0} = \alpha \left( 1 - \left( \frac{T}{T_c} \right)^2 \right)^{1.5} \]

where \( \alpha \) - fitting parameter.

The description of the heat transfer physics is based on the expression:

\[ \rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q \]

where \( C_p \)-heat capacity, \( \rho \)-density, \( k \)-coefficient of thermal conductivity of the used materials. In the right-hand side of equation (5), all heat sources \( Q \), including thermoelectric, located. In our case, in the absence of convective heat transfer, the main source of heating is the superconducting tape. Local heat generation in the system is calculated as:

\[ Q = E \cdot J \]
where $E$ is the electric field inside the superconductor. The current distribution $J$ of the superconductor is determined by the conditions of magnetization and is calculated as the solution of the Maxwell equations, realized in the PDE form. In addition, in modeling, the dependences of the heat capacity and the thermal conductivity on the temperature for the superconducting layer were taken into account [3]. For other tape layers, these coefficients were laid in the form of averaged values, characteristic for the selected temperature range. This assumption is correct due to a small temperature change of these layers when the tape is heated.

3. Results and discussion
The simulation of tape magnetization in an external uniform magnetic field for different magnetization velocities was carried out. The magnetization times were $0.5s$, $2s$, $10s$, $30s$, $60s$ the cooling temperatures – $40K$, $50K$, $60K$, $65K$, $80K$.

As expected, at lower temperatures the HTS sample traps larger magnetic field (Figure 2a). The maximum value of the trapped magnetic flux $H_{max} = 6.4*10^5 A/m (0.8T)$ at a height of $1$ mm from the surface of the tape for the magnetization duration $0.5s$ at $40K$. However, more intensive magnetization regime, leading to more intense heating, requires higher cooling power (Figure 2, b).

![Figure 2. Dependences of the trapped magnetic flux (a) and cooling power (b) on the temperature.](image)

Temperature maintenance for the short-pulse magnetization requires powers several orders higher, than for the long-pulse magnetization, while the trapped flux value increases only about 20%. This indicates the existence of an optimal magnetization regime for trapping the flux under the given magnetization and cooling conditions.

In addition, increasing of the magnetization velocity also leads to an increase in the trapped magnetic flux. Similar results for magnetization by single pulses were obtained experimentally [4]. Such magnetic behavior can be explained by the thermal processes occurring in the tape during the magnetization. At slow magnetization, heat flux has time to spread throughout the sample. Temperature increasing leads to a decrease in the critical current of the sample, and, consequently, to trapped flux decreasing. At short-pulsed magnetization, on the contrary, the thermal spot, that appears on the edges of the tape, does not have time to spread into the interior of the sample and does not affect its magnetic characteristics.

Figure 3a shows the temperature gradient dependences on the magnetization time for the $40K$ and $80K$ temperatures (applied field $0.5T$). It can be seen that when magnetizing with short pulses There are local hot regions with a temperature jump several times greater than in the case of slow magnetization. At the same time, at a lower temperature, a larger gradient appears.

Using the calculation model, it can be seen that the magnetic field begins to enter the HTS tape from the edges, where the maximum heat release occurs at the initial times (Figure 3, b). At the initial magnetization stages, the magnetic field $Hz$ and the gradient temperature field permeate the sample.
practically at the same time. Then the resulting thermal spot begins to propagate through the sample
due to the own thermal conductivity of the superconductor and the stabilizing layers. The main heat
outflow is through the substrate [5].

Copper coating contributes to the dissipation of the sharpest maximums of heat, thus, copper
performs a stabilizing function. Ultimately, thermal processes becomes steady and new temperature
bursts do not arise. The heat release along the edges of the tape continues until the magnetization
process is completed.

![Figure 3. Temperature gradient a) the dependence on the magnetization time, b) the "heat spot"
appearance](image)

4. Conclusions
Based on the use of the finite element method the physical model of the magnetic levitation system
element based on the second generation HTS tape was developed. The model uses the features of the
tape's layered structure. For the superconducting layer, the dependences of the heat release, cooling
power, and trapped magnetic flux on the temperature for different magnetization rates were obtained.

Obtained results indicate the existence of optimal parameters of temperature and magnetization
velocity to achieve the maximum performance of devices based on HTS tapes stacks.

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