Simulation of magnetization and heating processes in HTS tapes stacks

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Abstract. In this work we present a computational model for a magnetic levitation system based on stacks of 12 mm x 12 mm second generation GdBa$_2$Cu$_3$O$_{7-x}$ high temperature superconducting (HTSC) tapes. In our model we have used the magnetic and transport characteristics of real industrial HTSC tapes. The thermal properties of each layer of high-temperature superconducting tape and the features of the layered structure of whole stack have also been taken into account. The numerical simulation was performed using the finite element method. Distributions of both magnetic field throughout the space and the current in every tape of the stack were calculated for two cases: (i) cryocooler cooling mode and (ii) cooling in the liquid nitrogen. The magnetization curves of the stacks in external field of a permanent NdFeB magnet and levitation force dependence on the gap between the magnet and the HTS tapes stack in these cooling modes were obtained. We have calculated heat transfer and temperature distribution in the system taking into account the effect of thermal properties of Hastelloy substrate, as well as Cu and Ag stabilization layers on the cooling process and dynamic magnetization. Simulation results were compared with the experimental data and a good agreement with numerical ones was shown.

1. Introduction
Currently, the main construction material for levitation bearings and suspensions are bulk high temperature superconducting samples. But bulk HTS has several drawbacks such as brittleness, the complexity of sample preparation, when samples of desired shape are needed. Also the critical current density ($J_c$) of the bulk samples is significantly less than $J_c$ for the HTS tapes. Thus, an alternative way to construct levitation systems is to use HTS tapes stacks that has high strength, simplicity of thermal stabilization and the ability to vary the geometric parameters of the stack. The magnetic properties and levitation characteristics of the tapes stacks depend not only on critical characteristics of materials but also on its geometry (the number and shape of the tapes), conditions of magnetization and cooling. The present work is devoted to the development of a multiphysical numerical model that makes it possible to calculate the parameters of a magnetic system based on HTS tapes for two cooling modes: liquid nitrogen and cryocooler.

2. Computational model
The simulated magnetic-levitation system is a high-temperature superconducting tapes stack placed in a gradient magnetic field of a permanent magnet. The geometry of the system is shown in the Figure 1.
The measurements for the modeled stacks were performed on superconducting tapes produced by SuperOx (Russia) with the width of 12mm. Thickness of the superconducting layer GdBa$_2$Cu$_3$O$_{7-x}$ is 1 micron, and the tapes critical current is 300A (criterion 1μV / cm, 77K, self field). Each simulated tape contains a substrate, and also copper and silver thin layers, in addition to the superconducting layer.

To study the behavior of a HTS tapes stack in an external magnetic field a finite element method was used. The model was developed on the basis of the Partial Differential Equations (PDE) form of the Comsol Multiphysics software module.

In Comsol Multiphysics the general PDE standard equation is (1):

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

Here the dependent variable, magnetic field $u = H(\xi, \eta, \zeta)$, is chosen in the entire space. The parameters of equation (1) are chosen in such a way that equation (1) becomes Faraday’s law (2):

$$\nabla \times E + \frac{dB}{dt} = \nabla \times E + \frac{d(\mu_0 \mu_r H)}{dt} = 0,$$

where $E$ - electric field, $B$-magnetic induction, $H$- magnetic field, $\mu_0$ - relative permeability of free space, relative permeability for air and for superconducting elements $\mu_r = 1$. The specifications of the parameters in the equations (1) is given in [1].

The nonlinear resistance dependence on the current is given by the power law with the power 21, which is typical for the samples of HTS tapes. The current components are determined from the Amper’s law. On the boundary of the computational domain, the Dirichlet boundary conditions were used. The critical current density $J_{c0}$ is determined on the basis of the transport measurements of the used HTS tapes. Also, in this model it is taken into account the two-exponential dependence of the critical current on the magnetic field [2] and well-known temperature dependence of the critical current:

$$J_{c0} = \alpha \left( 1 - \left( \frac{T}{T_c} \right)^2 \right)^{1.5},$$

where $T$ is the temperature, $T_c$ is the critical temperature, $\alpha$ – a fitting parameter.

The description of the heat transfer physics (Heat Transfer in Solids module of the Comsol) is based on the expression:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-k \nabla T) = Q + \rho C_p u \nabla T,$$
where \( C_p \)-heat capacity, \( \rho \)-density, \( k \)-the coefficient of thermal conductivity of the materials used in this work, which depend on temperature for each layer [3], \( \mathbf{u} \) is the temperature velocity field, \( Q \) – all heat sources, including thermoelectric.

Local heat release in the system is calculated as:

\[
Q = E \cdot J
\]  

(5)

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.

Within the model, the cryocooler cooling mode realized by a copper bulk plate whose external boundary is set as a cooling source with a certain temperature. The heat radiation from the outer cryostat walls, which are at room temperature, is taken into account. Calculations determine the required power for the cooling element, which should not exceed the power of the real cryocooler-cooling system [4]. Otherwise, there is a violation of the temperature regime, which leads to undesirable heating in the system.

Simulation of liquid nitrogen cooling reduces to setting the heat transfer coefficient for the space region completely encompassing the HTS tapes stack [5] as oppose to the cryocooler acting from the bottom of the stack. Actually, we specify the heat transfer coefficient for the convective boiling of nitrogen taking into account the possibility of boiling nucleation with the other heat transfer coefficient [6].

The interaction force of the HTS tapes stack with the permanent magnet (the levitation force) is calculated as follows:

\[
\mathbf{F} = \int \mathbf{J} \times \mathbf{B} \, dV,
\]  

(6)

where \( \mathbf{B} \) is the magnetic field induction of the permanent magnet. The currents distribution \( \mathbf{J} \) in the superconducting tapes of stack was calculated as the result of the solutions of the PDE equations. Integration is performed over the entire volume of the superconductor.

Firstly, using the Rotating Machinery module of the Comsol Multiphysics software, the stationary study of the magnetic field distribution around the magnet was solved. Residual induction on the magnet surface must be in the range 0.30 - 0.35T, which corresponds to the experimental setup [7].

During the magnetization, the HTS stack slowly approaches the magnet (at a constant speed of 5mm/s), and then moves away from it in the same fashion (ZFC mode). To calculate the external magnetic field distribution during permanent magnet movement along the z axis we use the Moving Mesh module together with Rotating Machinery module. Obtained result can be applied as an external magnetic field on the next step – modeling the time dependent HTS tapes stack magnetization process.

It is notable that the last calculation step involves a simultaneous solution of all four modules used at the model. Equations (3) and (5) determine the interconnection of interfaces Heat Transfer in Solids and PDE. When currents appear in superconducting layers, heat release begins and the temperature of the tapes changes. This leads to changing in the critical current in accordance with equation (3). At the next solution time step, the new value of the critical current will be taken into account, so the simultaneous solution is more accurate than the segregated solution. However, the solution of such a simultaneous study requires large computing powers and requires much time. To reduce the calculation time, the functional dependencies on the number of tapes in the stacks were calculated in 2D mode. In 3D mode, some simplifications were also made: copper layers in each tape were specified as two-dimensional layers. Since these layers do not play a role in the magnetic fields physics, but have a great importance in the heat transfer in HTS tapes, their thickness was implicitly determined using Thin layer boundary conditions of Heat Transfer in Solids module.

Special attention should be given to the mesh construction (see fig.1). Using the multiscale structuring allows to thicken the mesh elements upon approaching to the sample, where the utmost accuracy of computation is required. In thin layers of the tape we have used swept tool for surface mesh. For the moving part of the model, the mesh of elements is rebuilt as soon as the quality of at
least one of elements decreases below the value 0.2 on a scale from 0 to 1, where 0 is an element of absolutely unsatisfactory quality, whereas 1 is an ideal equilateral element.

3. Results and Discussion

The magnetic properties of the tapes stacks for various height were calculated in two cooling modes: the cryocooler cooling mode and the liquid nitrogen cooling mode. In the liquid nitrogen cooling mode, the remnant magnetizations and levitation forces were calculated for stacks of tapes containing from 1 to 100 layers (Figure 2). The calculations results are in good agreement with the experimental data (more about the experiment see [7]).

![Figure 2. The normalized dependence of the magnetization (on the left) and the maximum repulsive force (on the right) on the number of tapes in a stack (inset: example of experimental and calculated curves for a stack of tapes containing 10 layers).](image)

The dependences of the maximum repulsive force and remnant field strength on the thickness of the stack have a similar behavior. These dependences behave almost linearly at small stack heights, but then the dependences tend to saturation. This indicates an inefficiency of using large tapes stacks to achieve the largest trapped flux and the repulsive levitation force.

![Figure 3. The normalized dependence on the number of tapes in a stack for liquid nitrogen and cryocooler cooling modes of trapped magnetic flux (on the left) maximum temperature gradient (on the right)](image)

The upper tapes of the stack are closest to the magnet and they appear in a higher external magnetic field, than bottom layers. These layers make the main contribution to the trapped magnetic flux. For
the given cooling parameters in the cryocooler-cooling mode, calculations show that the trapped flux increases only for stacks with small height. As a number of tapes in the stack further increases the trapped flux begins to decrease (Figure 3, on the left).

This behavior explained by the fact that cooling in a given mode is carried out only at the lower boundary of the stack, while the upper layers, which are most actively involved in the magnetic flux trapping, are at higher temperatures. From this point of view, nitrogen cooling for high stacks is more efficient. It should be noted that for a more powerful cryocooler-cooling (to temperatures of 65 K and 50 K), the magnetization drop with increasing number of tapes in the stack can be explained by the critical current increasing with decreasing temperature. In this case, a sufficiently weak permanent magnet magnetic field cannot penetrate into the tapes with higher critical current, and the tapes remain in the Meissner phase. Therefore, the maximum temperature gradient focuses on the edges of the stacks and increase with the grows of the stack height. (Figure 3, on the right). Despite the fact that the trapped flux is reduced substantially, the heat generation continues to rise. The magnetic field begins to enter the tapes from the edges, but it cannot enter into the tapes center which leads to more intensive heating at the edges of the stack. It is also worth noting that the significantly higher temperature gradient corresponds to a cryocooler cooling mode than to the liquid nitrogen cooling mode.

At the initial magnetization stages, the magnetic field $H_z$ 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. These data on the heat propagation in HTS tapes is also supported by other calculations [8]. The dynamics of the heat processes in the stack is somewhat different for the different cooling types. Figure 6 shows the dynamics of heat transfer processes in a stack of tapes containing 20 layers. The temperature change in such a stack is significant differ for the two considered cooling regimes (see Figure 3, on the right). Therefore, the data shown in Figure 4 is provided with different scales, which are convenient for illustrating the processes taking place in the tapes.

![Figure 4](attachment:FIG4.png)

**Figure 4.** Dynamics of heat transfer in the HTS tapes stacks in the cryocooler cooling mode at the temperature 77.4 K (on the left) and in the liquid nitrogen cooling mode (on the right). Cross-section of the stack of 20 tapes.

At the initial moments of time, the magnetic field reaches a HTS tapes stack and heat generation begins at the edges of the upper tapes. The power of the cryocooler cooling system is sufficient to cool the layers closest to the cooling source. If the stack height is increased, the upper layers will be at higher temperatures, which negatively affects the amount of the trapped flux, hence it would be decreased. It can also be noted that the strongest heating for the cryocooler cooling mode occurs only
at the edges of the stack. It can be assumed that for the efficiency of such cooling system it would be useful to cool not only at the lower boundary of the stack, but also along its lateral boundaries.

In the case of liquid nitrogen cooling, the stack of tapes, which is well cooled from all directions, turns out to be the most heated in its center. This turns out to be important for the stacks with only few tapes having a small height. For such stacks, cryocooling cooling mode is most effective, since it can maintain more uniform and constant shape of the temperature distribution throughout the stack during the magnetization. However, for the large stacks of tapes, nitrogen cooling is more promising. This can also be seen from the value of the trapped flux of HTS stacks of tapes (Figure 4).

4. Conclusions

By using the finite element method, the physical model of the magnetic levitation system element based on the second generation HTS tapes stack was developed. The model takes into account the real features of the tape's layered structure. In the frame of our model, the dependences of magnetization and the levitation force on the number of tapes in a stack in a gradient magnetic field of a permanent magnet were calculated. The dependence of the maximum repulsive force and the magnetization in ZFC mode on the thickness of the stack of tapes is non-linear. It also reaches a saturation for stacks of about 60-100 tapes. The comparison of the computational results and the experimental data shows consistent results.

The advantage of developed model is the possibility of changing all input parameters of the system, as well as properties of HTS samples, and also in the model we calculated real movement of the magnet, which makes the model applicable to the calculation and optimization of magnetic and levitation systems of various configurations. This may be useful in the fields of building new transport systems of various scales, electrical rotating machines, such as wind turbines, and other energy generators and energy storage.

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