Simulation of Thermal Processes in Superconducting Pancake Coils Cooled by GM Cryocooler

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Abstract. This article presents the thermal model of a small scale superconducting magnetic energy storage system with the closed cycle helium cryocooler. The authors propose the use of contact-cooled coils with maintaining the possibility of the system reconfiguring. The model assumes the use of the second generation superconducting tapes to make the windings in the form of flat discs (pancakes). The paper presents results for a field model of the single pancake coil and the winding system consisting of several coils.

1. Introduction

Superconducting magnetic energy storage systems (SMES) are one of the most interesting and attractive applications of superconducting materials. Energy is stored in the form of magnetic energy generated by the dc current flowing through the superconducting coil. The first concepts from early 1970s assumed the construction of large plants that would store hundreds of megawatt hours of energy [1]. Currently designed SMES are used rather to minimize the effects of voltage fluctuations and are characterized by low dimensions and a small quantity of stored energy [1-4]. The main advantage of SMES systems, compared to the other storage systems, is fast, reliable and flexible power compensation in power systems. Therefore, SMES help to improve the quality and stability of power systems. A typical SMES consists of the following components: the superconducting coil (electromagnet), the power conditioning system (energy converters), the control unit and the cryogenic system [2]. The contact cooling method, used in designed system, imposes numerous restrictions in the design of the coils, current leads and cooling system, but it is the most economical and safe method for temperatures lower than 40 K.

In this article, the authors focused on the modelling of the cooling process of the high-current coils made of the second-generation (2G) ReBCO superconducting tapes. Currently, the winding of the pancake (flat) coils is the most popular method of winding coils from 2G tapes. Depending on the application, superconducting windings are configured in the form of a stack (high magnetic field electromagnets) or the form of a toroid (SMES). ReBCO compounds exhibit a lower anisotropy of the crystal structure and of the electronic properties in comparison to BSCCO compounds. It implies a stronger coupling of vortices to form flux lines, a lower tendency to flux creep effects and a much larger irreversibility field [5]. Preparation methods of ReBCO tapes (depositing, coating) allow to obtain the high-quality, oriented superconducting films with a limited number of the weak links amongst grains. Therefore, 2G tapes offer unprecedented electromagnetic (very high critical current and upper magnetic field) and also mechanical (high tensile strength and mechanical stability)
parameters. The great advantage of the 2G tapes is also high thermal stability resulting from the very small thickness of the superconducting ReBCO layer (about 1 µm) in relation to a substantially thicker layer of metallic substrate (tens of µm) [6]. The temperature margin for coils made of high temperature superconducting materials is greater by an order of magnitude in comparison to the low temperature superconductors and the heat capacity is greater by 2-3 orders [7]. Favorable electromagnetic, mechanical and thermal parameters of new generation tapes allow building devices with much smaller dimensions (e.g. integrated with a closed cooling system using helium cryostat). These solutions may be significantly less complicated in comparison to cooling systems with cryogenic liquids. The winding construction should provide a high thermal stability in the static and dynamic states at large currents and a sufficiently mechanical stability, which provides a small degradation of the winding insulation. The authors propose the use of contact-cooled coils with maintaining the possibility of reconfiguring the system.

The initial cooling process plays a key role in the operation of magnet systems cooled by crycoolers [8]. The functionality of the system is significantly determined by the initial cooling time. The paper presents results (dynamics of cooling process) for a field model of the single pancake coil and the winding system consisting of seven coils.

2. Analysis of thermal processes

Analysis of the nature of thermal processes in the vacuum-insulated cryostat was first and crucial stage of the work. Contact cooling requires a special construction of the cryostat, in which the cooled element is placed in a vacuum, which is the main insulation [9]. The heat exchange between the cooled parts and the head of the cryocooler is carried out by heat conduction. A good connection between the heat exchanger and the cooled part and the effectiveness of thermal insulation from the environment are key factors in designing of the cooling system. The factors that may influence the cooling efficiency in this method are:

- maximum heat load of the cryocooler, which results directly from the type and construction of the device. The heat load is strongly temperature-dependent and decreases with decreasing temperature;
- heat capacity of the cooled part, which is directly related to the mass of the part and its specific heat capacity, which depends on the amount and type of used material. Copper is the most common used material because of the high thermal conductivity and relatively low price;
- the quality of the connection between the cooled part and the cooling head. Thermal resistance of the connection should be minimized and constant in the wide temperature range (especially at low temperatures). The contact surface should be as large as possible, to reduce the heat flux density. The soft indium foil is used to create “seals” in such cases [10];
- thermal insulation. Vacuum insulation (reducing heat conduction in the gas) and the radiation shields are the most commonly used methods of reducing heat exchange with the environment.

Optimal construction of the cooling system should eliminate uncontrolled heat transfer inside the cryostat, i.e. radiation and convection in the gas. The existence of a small amount of gas in the vicinity of cooling head and cooled parts leads to the occurrence of convection, which can be considered as a combination of the thermal conductivity of the gas and the dynamics of movement of its particles. The reduction of gas pressure in the cryostat greatly reduced heat transfer by convection of gas. This is due to the increase in the mean free path of gas molecules resulting from the reduction of pressure and temperature.

Radiation is the dominant mechanism generating losses in cryogenic systems. Thermal radiation is the energy emitted in the form of electromagnetic waves by a body having a specific thermal energy at a given temperature. The energy transport by radiation does not require a medium, however it plays a dominant role in vacuum cryostats. The use of metal shields of highly reflective material and decreasing the emissivity coefficient are the most effective methods of reducing radiation [11]. The
surface quality of the used materials is particularly important. Materials coated with oxides and matt surfaces are particularly disadvantageous.

3. Experiment
The authors intend to design and make the operating, micro superconducting energy storage system. This paper describes the first stage of the project, i.e. developing the concept of the implementation of windings, current leads and the cooling. The system uses the closed cycle helium cryocooler ARS DE-210AF with compressor M600. The applied cryocooler is a two-stage Gifford-McMahon refrigerator, characterized by high refrigeration power (25W at 77 K – on the first stage and 4W at 9K – on the second stage). The workspace in the radiation shield has the diameter of 170 mm and the height of 100 mm.

In the first part of the experiment, the authors have determined characteristics of the cooling process with variety geometries and heat capacities of the heat load. The objective of this study was to analyze the dynamics of cooling. The combinations of two heat exchangers: a copper block (80x80x10 mm) and a copper disc (140x10 mm) were examined. The exchangers were mounted directly on the cold finger of the cryostat. An indium foil was used to seal the connection. The study involved three load configurations: block, plate, block placed on the plate (figure 1).

![Figure 1. Heat load configurations: (a) copper block, (b) copper plate, (c) block placed on the plate.](image)

The measured time of cooling the exchanger depended mainly on the heat capacity of the entire system and the initial temperature. The cooling time increased together with the increasing of the heat load, but the nature of the process remained unchanged. This indicated a good tightness of the vacuum system and a proper selection of the radiation shields. The process was linear up to approx. 40 K, then it was characterized by a much higher dynamics (figure 2).

![Figure 2. Dynamics of cooling process on cold finger obtained for actual system and determined from model (various configurations of heat exchanger).](image)
This change can be identified with the increase of thermal conductivity of copper, typical for this range of temperatures, and the change of the kinetic energy of gas molecules due to lower temperatures, which transfers into a deceleration of the gas molecules, and means the additional reduction in the gas pressure. The study was carried out in a medium vacuum at a pressure of 60 mTorr and at the initial temperature of 295 K.

The experimental demonstration of the dominant role of radiation as a source of heat loss in vacuum cryostats was the next stage of the research. The plate+block configurations with and without the radiation shield were examined (figure 1c). Only the upper part of the shield covering the exchanger was removed. Temperature of the cold finger and temperature on the surface of the heat exchanger were measured. Removing the radiation shell impeded the cooling process particularly in the low temperature range (figure 3). For the system without the radiation shield the temperature of the exchanger could not be reduced below approx. 85 K. The increase of temperature of the heat exchanger extended the time of cooling the cold finger. This confirms the domination of the radiation process at low temperatures in vacuum cryostats.

In the second part of the study the authors have made the prototype of the device with a single superconducting coil (figure 4). The cold finger of cryostat was attached to a heat exchanger in the form of a circular disc (diameter 140 mm, height 10 mm), made of electrolytic copper. The flat superconducting coil (45 turns, outer diameter 105 mm, inner diameter 75 mm) was attached to the heat exchanger.

![Figure 3. Time dependence of temperature at cold finger and surface of heat exchanger with and without radiation shield.](image)

![Figure 4. Prototype device - superconducting coil attached to heat exchanger.](image)

![Figure 5. Dynamics of cooling of single coil attached to copper plate obtained from experiment and from simulation (temperature is measured at cold finger).](image)
High heat capacity of the heat exchanger ensured high thermal stability of the operation of the winding. The current leads were made of flat copper bars. The contact surface between leads and the heat exchanger was as large as possible. The solution minimized the amount of heat transported to the coil from the environment through current feedthroughs. Kapton tape of a thickness 50 microns was used for electrical insulation. The superconducting coil with cooled current leads adds small heat load to system. It results from their small heat capacity in relation to the heat exchanger. Thus, the cooling time is only slightly longer (about 5 minutes) in comparison to the cooling time of the heat exchanger (figure 5).

4. Models
Further design work was preceded by the development of thermal and electrical model of the designed device. The model was implemented in COMSOL Multiphysics package [12]. The primary objective of this part of the work was the developing an universal model, accurately describes the thermal processes occurring during the cooling in the cryocooler. Empirical studies carried out for various loads and various geometries were the knowledge base required to develop the model. The model allows to determine the cooling time of components with different geometries and made of different materials and determine the most basic thermal parameters of the analyzed systems. The model also enables an analysis of the dynamics of the process. The possibility of extending the described processes with phenomena related to the electric current flow and the Joule heat generation is an additional feature of the model. The study was divided into two sub-steps. During the first, geometries corresponding to systems tested empirically were examined (figure 1). In the second part the geometry of the superconducting magnet with the pancake coils (part of SMES) was analyzed.

Heat transport is described by the conventional heat equation [12]:

$$\rho C_p \frac{\partial T}{\partial t} -\nabla \cdot (k \nabla T) + Q,$$

where \( g \) is the density of the solid; \( C_p \) is specific heat; \( T \) is the temperature, \( k \) is thermal conductivity, \( u \) is the velocity vector of particles and \( Q \) is the heat source. The convection can be neglected for solids (\( u=0 \)), therefore equation (1) can be converted to the following form [12-14]:

$$gC_p \frac{\partial T}{\partial t} -\nabla \cdot (k \nabla T) = Q.$$  

The \( Q \) term represents Joule heating and can be described as follows:

$$Q = E \cdot J,$$

where \( E \) is the electric field strength (\( V - \) electric potential):

$$E = -\nabla V,$$

\( J \) is the total current density (\( \varepsilon - \) the electric permittivity, \( \mathbf{J}_e - \) externally generated current density) [11]:

$$J = \left( \frac{1}{\rho} + \varepsilon \frac{\partial}{\partial t} \right) E + \mathbf{J}_e.$$

All the parameters of the materials used in the model are temperature dependent (figure 6). Taking into account the effect of the temperature on materials parameters is necessary to preserve the accuracy of the model. It results from the strong influence of temperature on the parameters of copper in the range \( T <100K \) (increase of the conductivity and decrease of the specific heat – figure 6). Moreover, copper is the predominant material in 2G superconducting tapes (over 50% of volume) and is a mechanical and thermal stabilizer for superconducting core. Therefore, the model can ignore the impact of temperature on the parameters of the superconducting core and buffer layers, however, it is
necessary to take into account the temperature dependence of physical parameters of copper and Kapton insulation. Adequately to the experimental studies it was assumed that heat exchangers are made of copper. The model takes into account two mechanisms of heat exchange with the environment: convection in the gas at reduced pressure and radiation. The boundary conditions for the thermal model (the heat flux on boundaries) are defined as follows [12]:

\[-\mathbf{n}(-k\nabla T) = q_0 + h(T_{\text{inf}} - T) + e\sigma(T_{\text{amb}}^4 - T^4),\]  

(6)

where \(\mathbf{n}\) is the unit vector normal to a boundary surface, \(h\) is the heat transfer coefficient, \(q_0\) is the inward heat flux, \(T_{\text{inf}}\) is the ambient bulk temperature, \(T_{\text{amb}}\) is the temperature of the surrounding radiation environment, \(e\) is the emissivity coefficient, \(\sigma\) is the Stefan–Boltzmann constant. Convection cooling is modeled by Newton’s law of cooling \(h(T_{\text{inf}} - T)\). The value of the heat transfer coefficient depends on many factors, i.e. the surface temperature, properties of the cooling fluid (e.g. pressure), the fluid’s flow rate and also the geometrical configuration. The general form of the coefficient \(h\) can be written as follows [12]:

\[h = \frac{L}{k}\text{Nu(Ra, Pr, Re)},\]  

(7)

where \(L\) is the characteristic length (e.g. length of wall); Nu, Ra, Pr, Re – characteristic dimensionless numbers: Nusselt, Rayleigh, Prandtl, Reynolds. The characteristic numbers depend on the of convection conditions and are described by, often complex, empirical and theoretical correlations. The phenomenon of the natural convection was taken into account using Comsol module, which allows to determine the convection coefficient based on the shape and dimensions of the elements (for vertical and horizontal walls) and the pressure of the surrounding gas. The pressure value was obtained from experimental studies (60 mTorr). However, in described case the heat transfer is mainly determined by the radiation mechanism. The model assumes that the heat emissivity coefficient \(e\) of the shield is constant and equals to 0.07 (polished Cu).

The connection between the heat exchanger and the cold finger is also included in the boundary conditions. The heat transfer at the connection is described as a heat flux directed from the heat exchanger through the surface corresponding to the contact with the cold finger (\(q_0\) is negative). The heat power transferred from the heat exchanger is described by the thermal dependence of the cryocooler heat load, provided by the manufacturer (figure 7) [19]. This assumption was necessary because the characteristics of the heat load is determined for the load applied to the cold finger and does not consider the heat capacity of the cryocooler elements as a separate factor. Thus, the geometry of the cold finger cannot be included in the model. The result of this assumption is inability to take into account an effect of the quality of the connection between the heat exchanger and the cold finger.

Figure 6. Temperature dependencies of thermal properties of copper: \(C_p(T)\) - heat capacity [15], \(k(T)\) - thermal conductivity [16,17], \(\rho(T)\) - density [16,18].
Thermal resistance of the connection produces a difference between the temperature of the finger and the temperature of the heat exchanger (figure 3).

The electrical boundary conditions assume electric insulation at all boundaries, with the exception of the single surface of current leads. The current flows into the first lead. The electric potential at the second lead equals zero.

The model is solvable despite the relatively complex geometry (figures 1, 8, 9), e.g. for a model shown in figure 9 the number of elements is 184412, the number of boundary elements is 54651. Calculations were performed using the iterative multigrid solver and FGMRES method. The computation time for the model with temperature-dependent parameters (analyzed period 0...80000 s) was 2382 s, for the model additionally taking into account the current flowing was 4379 s (Intel(R) Xeon(R) X3440 with 12 GB RAM). The main objectives of modelling were the investigation of the cooling process, the comparison with the actual results and the assessment of the reasonableness of further development of the project.

Figures 2 and 5 show the comparison of the dynamics of the cooling process for the actual systems with various configurations of the heat exchanger (including a coil) and the results obtained for the numerical model (temperature 20K is reached after approx. 80 minutes). The simulation results are consistent with the results of the experiment. It confirms the validity of the used assumptions.
Basing on the model with a single coil (figure 8), an extended model with seven coils was developed in the next step (figure 9). The model assumes that the pancake coils (130 turns) are wound from 2G superconducting tapes with the copper stabilizer of a width of 12 mm. In order to improve cooling efficiency and ensure the mechanical stability the coils were placed in the copper cassettes. The windings are configured in a stack and placed on a heat exchanger (copper plate) with the parameters given in the previous model. The designed system is adapted to work with the current of about 500 A and requires a different design of the current leads with increased cross-section. The proposed high current leads are cooled by the contact method with the side surfaces of the heat exchanger (figure 9).

Figure 10 shows the temperature distribution in the cross-section of the device, obtained after a period of approximately 11 h. The presented distribution is uniform throughout the entire volume of the windings (21 K). It confirms the suitable thermal stability of the system.

![Figure 10. Temperature distribution after approx. 11 hours of cooling (I = 0 A).](image1)

![Figure 11. Dynamics of cooling of SC-magnet (temperature is measured at cold finger) and current-time characteristic.](image2)

Figure 11 presents time dependency of the temperature at the cold finger for SC-magnet. The model assumes that the current in windings increases with a small slope (di/dt = 1 A/s) (figure 11d), therefore the losses resulting from eddy currents are negligibly small. The coil current causes Joule heating and is the main reason of extending the cooling time (figure 11b). In addition, the change of material properties (figure 6) and the crycooler heat load (figure 7) influence on the process. In order to investigate the effect of variability in material parameters the simulations for constant values were carried out. In this case, the simulated cooling time significantly increased and the nature of the process was changed (figure 11c). This result is inconsistent with the experimental results. The time of current switching is the most important in the cooling of magnets. It confirms the crucial role of the initial cooling in the operation of the magnet [8].

5. Summary
Application of 2G superconducting tapes to build superconducting magnetic energy storage systems can reduce device size while maintaining operating parameters. Large usable critical current density and high thermal stability of these tapes allow for the construction of small-size devices, which promotes the use of cryocoolers and contact cooling - simple in design or operation and economical refrigeration method. The main distinction of cryocoolers is that cooling is provided by a closed loop system, which eliminates the cost of the continuous supply liquid helium. Contact cooling in contrast to cryogenic cooling in liquid ensures full control over the operating temperature of the
superconducting device. In the case of superconducting magnetic energy storage, it transfers into the amount of accumulated energy.

A significant reduction in the temperature of the coils, below the critical temperature of the superconductor (93 K for 2G YBCO tapes), increases the current density of the superconducting tape, and consequently increases the capacity of the energy storage. It also significantly increases the thermal stability and the safety margin of the windings, which is especially important in dynamic states of high-current devices. A comparison of temperature dependencies of the relative value of the critical current and the magnetic energy shows that cooling of the windings below 20 K will not substantially increase the amount of the accumulated energy.

The presented model correctly describes the thermal processes occurring in the cryostat with vacuum insulation. The obtained results are consistent with the results of physical experiments carried out on different shapes and different volume of cooled elements. It confirms the versatility of the proposed description and the possibility of using the model to describe the thermal processes occurring during the cooling of components with any geometry including SMES. It should be noted that the parameters used in the model, such as gas pressure, the emissivity of the shield, and others correspond to the physical experimental system. Model has not been validated for other configurations.

Well defined thermal model enables qualitative and quantitative analysis of cooling process and optimization of the device design. Experimental verification of the model with a single coil confirms the validity of the assumptions. The presented model is the basis for constructing more complex models of superconducting systems cooled by cryocoolers. For a model with seven coils resulting time to cool down to the temperatures about 20 K is much longer (over 11 hours). Therefore, the presented model requires further optimization, especially reducing the volume of stabilizer.

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