NbTi Magnet Cooled by SRDK-408 Cryocooler - Results and Numerical Model

S. Kozak, T. Janowski, G. Wojtasiewicz, B. Kondratowicz-Kucewicz, J. Kozak, and P. Surdacki

Abstract— **Cooling down to the operation temperature and keeping the temperature on adequately low level by good thermal insulation and good cooling conditions decide on superconducting state in a superconducting device. In low temperature below 150 K significant changes of electrical and thermal parameters vs. temperature are observed. The paper presents the numerical model in FLUX2D of cooling a superconducting NbTi magnet (mass = 1.46 kg) for an OGMS separator using the SRDK-408 cryocooler. The USER SUBROUTINES were used to define advanced temperature relations of physical properties in calculated regions and thermal flux to the cryocooler. Experimental results were used to verify the parameters of the numerical model. The NbTi magnet needs around 6 hours for achieving superconducting transition, but only 1 h and 40 min to reach 30 K.**

Index Terms— **NbTi magnet, numerical model, cryocooler, FLUX2D.**

I. Introduction

THE NbTi magnet for OGMS (Open Gradient Magnetic Separation) separator was successfully investigated for cleaning industrial water from iron particles with diameters from 5 µm to 20 µm [1]. The recovery up to 92 % and the efficiency up to 12 m^3/h have been obtained in the experiments. The operating principle of the OGMS separator consists in the selective deflection of particles, according to their magnetic susceptibility, during their passage through a strong, nonhomogeneous magnetic field generated by a magnet. The magnet of the OGMS separator consists of two coaxial and adjacent NbTi coils. This NbTi magnet was constructed for bath-cooling technique. Because of Al-alloy mandrel and winding without cooling channels this NbTi magnet has features of conduction-cooling by a cryocooler. Numerical model of conduction-cooled LTS magnet verified by experimental results of a small LTS magnet for OGMS separator can be easily used for numerical investigation of larger LTS or HTS magnets.

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II. NbTi Magnet

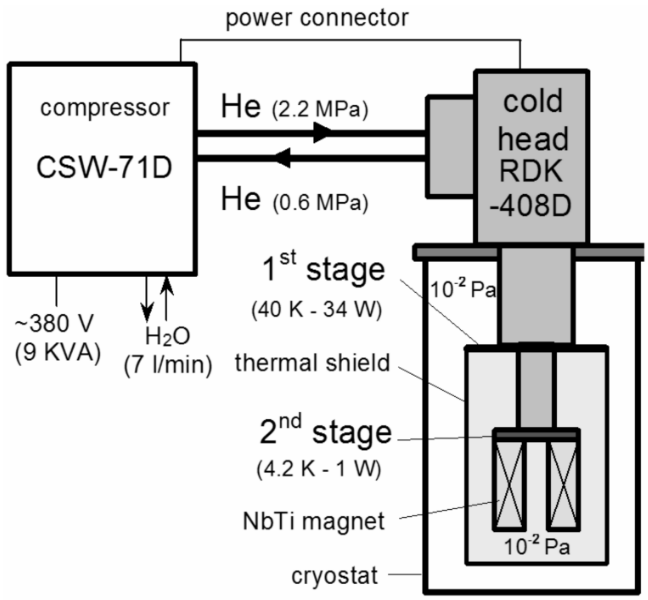

Fig. 1. The NbTi magnet with a cooling system using the SRDK-408 cryocooler.

TABLE I
PARAMETERS OF NbTi MAGNET OF OGMS SEPARATOR [2]

Name	Value
Distance between coils	0.01 m
Inner radius of coils	0.0314 m
Outer radius of coils	0.0389 m
Length of coil	0.04 m
Operating current	±250 A
Maximal magnetic field	2.26 T
Winding package factor	0.32
Average current density	$\pm 4.17 \cdot 10^8$ A/m^2
Mass of magnet	1.46 kg
Resistance at 293 K	19.8 ohm

Fig. 1 presents the NbTi magnet in a cooling system with the SRDK-408 cryocooler. The NbTi magnet is connected to the second stage of the cryocooler and the thermal shield is connected to the first stage (Fig. 2). Top part of the thermal shield is equipped with supports for Bi-2223 current leads.

The one-piece Al-alloy mandrel of the NbTi magnet (Fig. 3) secures a good thermal connection between the superconducting coils and the second stage of the cryocooler.

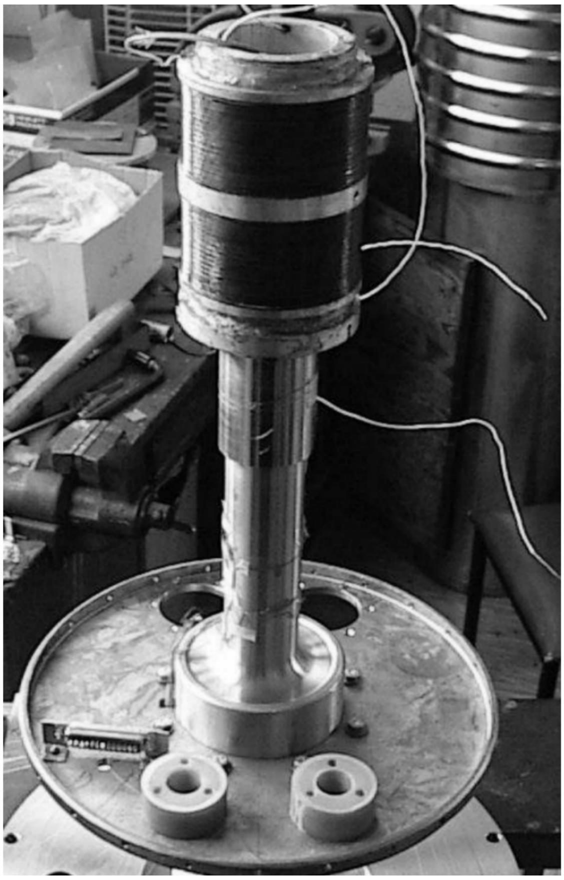

Fig. 2. NbTi magnet connected to the second stage and top part of the thermal shield connected to the first stage of SRDK-408 cryocooler.

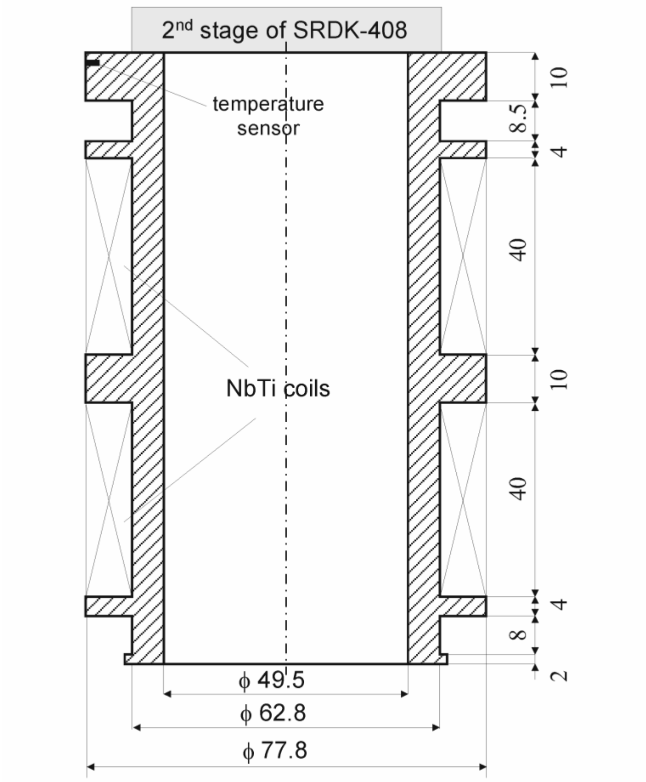

Fig. 3. AL-alloy mandrel of the NbTi magnet. Dimensions in mm.

III. Experimental Results

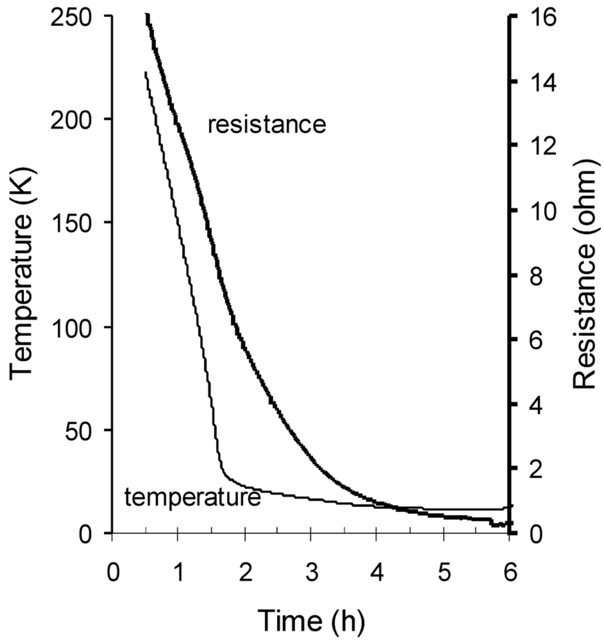

Fig. 4. Temperature and resistance during cooling down of the NbTi magnet.

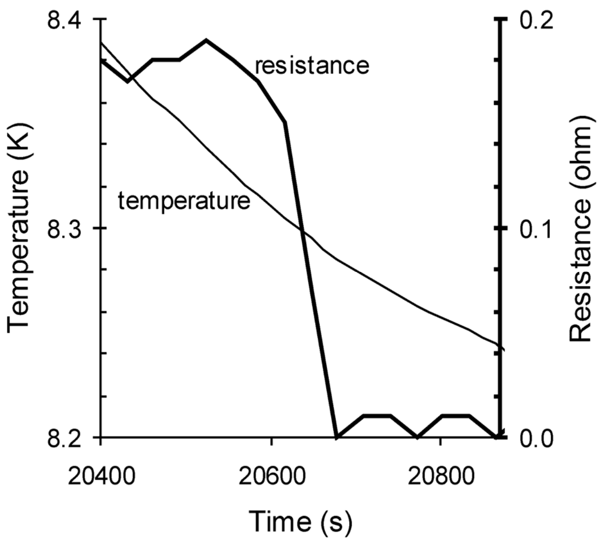

Fig. 5. Temperature and resistance during superconducting transition of the NbTi magnet.

Fig. 4 presents temperature measured in place shown in Fig. 3 and resistance of the NbTi magnet during cooling process. The data acquisition of temperature with a 218-Temperature Monitor and computer system [2][3] started at 1800 s after turning on the cryocooler. Fig. 5 shows temperature and resistance of the NbTi magnet during superconducting transition.

IV. Numerical Model

The values of thermal parameters of materials used in superconducting devices at low temperature below 150 K have

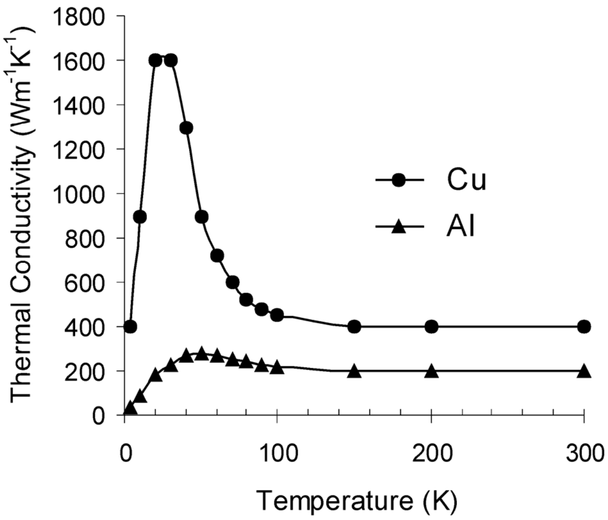

Fig. 6. Thermal conductivity vs. temperature for Cu and Al.

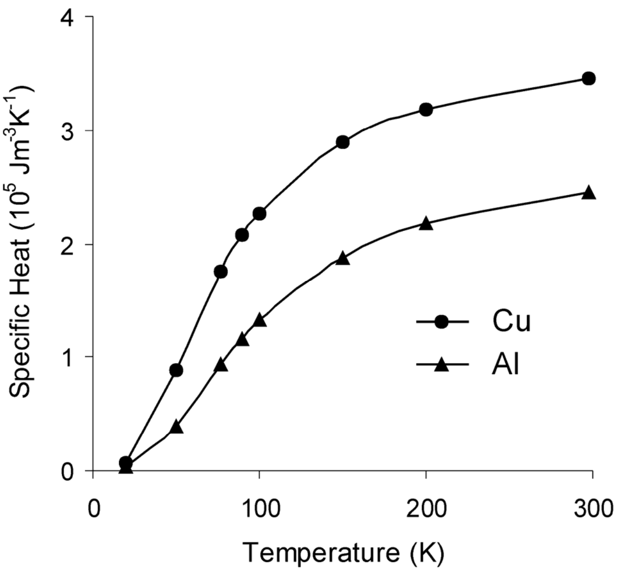

Fig. 7. Specific heat vs. temperature for Cu and Al.

very significant changes, vs. temperature. Additionally, the shapes of these changes are in general significantly different from those predicted by FEM CAD packages. Figs. 6 and 7 present values (used in numerical model) of thermal conductivity and specific heat of copper and aluminum vs. temperature [5][6]. Presented (in Figs. 6 and 7) shapes of those parameters are average for copper and aluminum because there are strong dependences of parameters values due to purity. According to Fig. 6, the maximal value of thermal conductivity of copper equals 1600 $Wm^{-1}K^{-1}$, however this value can vary from 800 $Wm^{-1}K^{-1}$ to 15000 $Wm^{-1}K^{-1}$ [6].

Numerical model of contact-cooled NbTi magnet was made using transient thermal modules of FLUX2D [4]. The user subroutines [4] USRKTH and USRRCP were used to define thermal conductivity and specific heat in calculation regions in numerical model geometry which is presented in Fig. 8. The

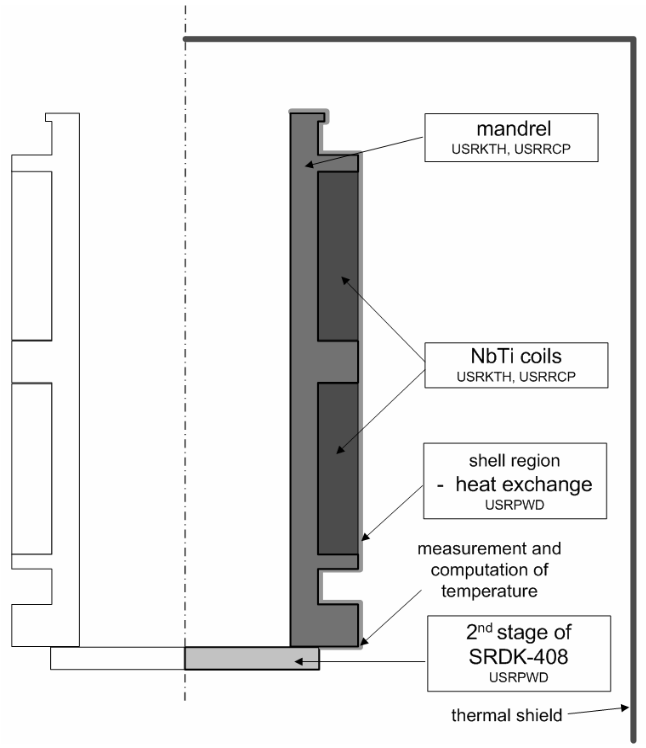

Fig. 8. Geometry of numerical model in FLUX2D.

USRKTH and USRRCP have two parameters. The first one defines the kind of material: Cu or Al. The second one defines value of winding package factor [7]. The numerical model consists of 4 calculation objects: the second stage of SRDK-408 cryocooler, the mandrel of magnet, the NbTi coils and the heat exchange. We assumed that mandrel had thermal properties as presented in Fig. 6 and Fig. 7 for aluminum. We also assumed that NbTi coils had properties as presented in Fig. 6 and Fig. 7 for copper. The coils are not uniform and we have assumed that winding package factor of this region is proportional to that shown in Table I.

Heat flows from NbTi coils to the second stage of SRDK-408 cryocooler through mandrel by conduction and radiates from shell region to thermal shield. The direction of heat radiation depends on gradient of temperature between shell region and thermal shield. Due to higher cooling power, the first stage and the thermal shield connected to it are cooled down faster than the second stage in the initial period of cooling process (Fig. 9). After about half an hour the second stage starts becoming colder than the thermal shield, and the heat radiates from it to magnet. Thermal source density of the second stage and thermal flux from shell region are defined in USRPWD subroutine. USRPWD subroutine has 7 parameters to define properly advanced temperature dependence of source density and thermal flux based on scanty data of cooling power of SRDK-408 cryocooler [8] and on experimental results [2][3].

Fig. 9 presents the temperature of the first and the second stage of SRDK-408 cryocooler without the magnet [3] and the temperature of NbTi magnet, measured and computed in

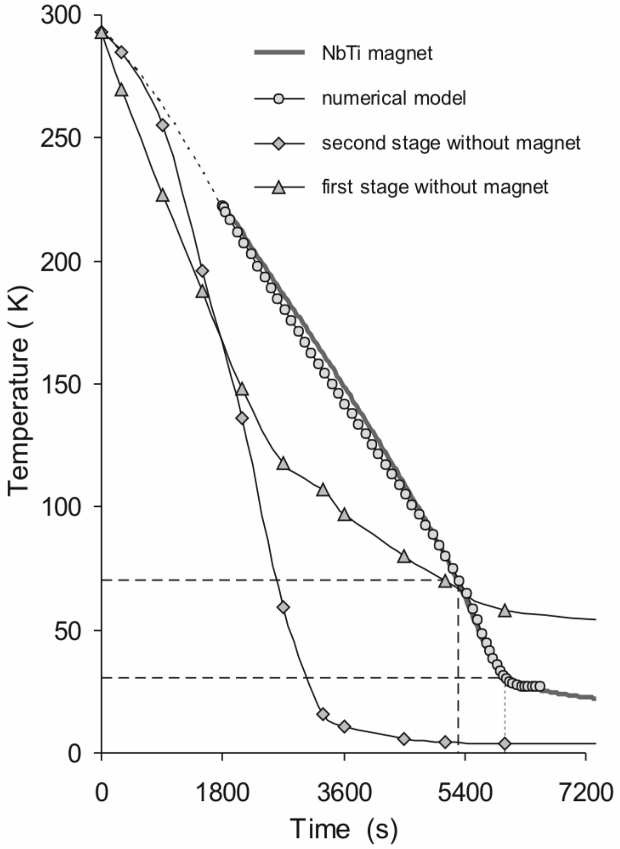

Fig. 9. Temperature of the first and the sesond stage of SRDK-408 without magnet and temperature of NbTi magnet.

place shown in Fig. 8. Experimental and computational results show good correlation of temperature during the cooling process of NbTi magnet. The increase of cooling speed between 70 K and 30 K (from 5300 s to 6000 s), in spite of decreasing cooling power, is caused by negative derivative of thermal conductivity (Fig. 6). When this negative derivative of thermal conductivity appears during computation, the solver of FLUX2D starts increasing the computation step uncontrollably and generating computation error. It is necessary to set proper computation parameters to solve this problem. After interruption we start computation with step = 1 s and limitation for step = 10 s.

V. Conclusion

The experimental results show that temperature of 4.2 K can be reached (using SRDK-408 cryocooler) after 5100 s when cooled object is very small (Fig. 9, without magnet). The NbTi magnet (1.46 kg) needs about 20 600 s (5 h 43 min 20 s) for achieving superconducting transition (Fig. 5) but only 5300 s to reach 70 K and next 700 s to reach 30 K (Fig. 9). Below 30 K cooling process becomes very slow. The fast reach of 30 K can be very useful in case of HTS magnets.

Numerical model of a conduction-cooled NbTi magnet was made using transient thermal module of FLUX2D. Lack or insufficient data are the main reason of difficulty in defining thermal properties and parameters of thermal sources of calculation regions. Physical properties were defined by 2-parametric subroutines USRKTH and USRRCP with winding package factor.

Thermal source density and thermal flux to SRDK 408 were defined by multi-parametric USRPWD subroutine.

Computation error due to negative derivative of thermal conductivity can be eliminated by proper computation parameters in FLUX2D solver.

The computational results of numerical model of conduction-cooling process of NbTi magnet are convergent to experimental results.

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