Design and Testing of a New Cooling System using Solid Nitrogen for Pulsed Field Magnetization and Characterization of HTS Bulks

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***Abstract*— Solid Nitrogen (SN_2) can provide a uniform and stable cryogenic environment for High Temperature Superconducting (HTS) systems such as bulk samples during their magnetization and/or characterization. In this paper, we are studying a SN_2 cooling system consisting of a cryocooler Sumitomo CH-110 and an exchanger in a Liquid Nitrogen (LN_2) bath. In order to design this cooling system, an analytical model based on a nodal method coupled to a formulation of the thermal capacity was realized. The model considers the thermal parameters variation as well as the phase change of the Nitrogen. In order to compare our results, we performed a 3D simulation on COMSOL Multiphysics. The performance of the cooling system was evaluated and we estimates that 50 L of LN_2 can be cooled down to 20 K in 50 hours.**

Keywords—Cryogenics, Solid Nitrogen, Liquid Nitrogen, Phase change, Analytical modelling.

I. INTRODUCTION

As shown in [1], thermal effects are the greatest limitation for controlling the magnetization of superconducting bulks during a Pulsed Field Magnetization (PFM) method. The performances of High Temperature Superconductors (HTS) are enhanced by decreasing their operating temperature [2]. Thus, we aim to obtain a more comfortable environment by freezing and cooling a Liquid Nitrogen (LN_2) bath down to 20 K.

Several methods have been developed to study the phase changes of materials. The present enhanced enthalpy method being a theoretical basis for the description and prediction of complex cooling and thermal processes [3]. Some others have proposed a stepwise thermal analysis of a cooling, i.e. thermal capacities are defined for each phases [4]: liquid, solid, and solid under 35.6 K.

In this paper, a whole cryogenic system for freezing LN_2 is studied. It consists in a cryostat, manufactured by Cryo Diffusion, a Sumitomo CH-110 cryocooler and a homemade Oxygen-Free High thermal Conductivity (OFHC) heat exchanger as shown in Fig. 1.

We simulate the cooling and freezing process from an analytical nodal method coupled [5] with a Heat Capacity Formulation (HCF). We also compared our model with a numerical simulation based on a 3D Finite Element Method (FEM) implemented on the COMSOL Multiphysics software.

II. COOLING SYSTEM

The heat transfer from the cold head to the LN_2 bath is achieved by thermal conduction thanks to a proper heat exchanger. The cooling system Fig. 1(b) consists of a 5 mm thick square plate of 440 mm side length. The choice of this shape was made in order to homogenize the temperature in the radial direction since the cold head is not located at the center of the system. Four 540 mm long rods with a 30x30 mm² square cross-section are then placed on the bottom of the LN_2 bath and connected to the thick square plate using flexible thermal links. The four rods are brazed using silver on the heat exchanger, which is made from a copper plate of 1 mm thick, 150 mm wide and 2 m long. This heat exchanger was manufactured in our laboratory and corrugated in order to increase the heat exchange surface. The whole set of copper parts weighs about 40 kg.

III. ANALYTICAL MODEL

A. Heat diffusion

The temperature variation of each element is calculated using a nodal method. A network of thermal resistors and

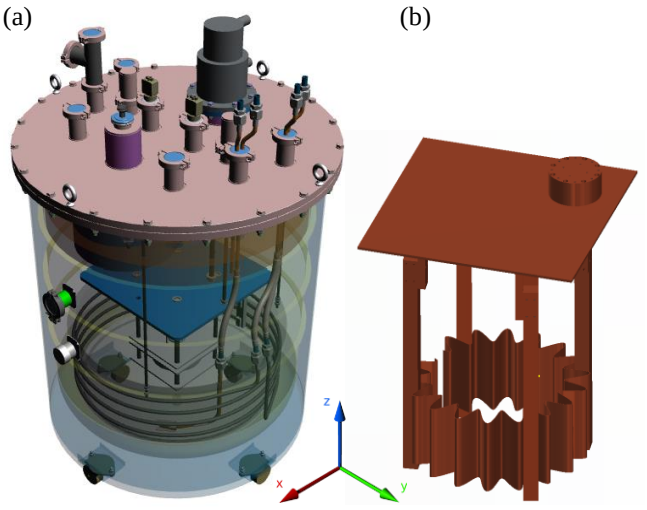

Fig. 1. Cryostat manufactured by Cryo Diffusion (a), and the heat exchanger designed to solidify nitrogen by using a Sumitomo CH-110 crycooler (b).

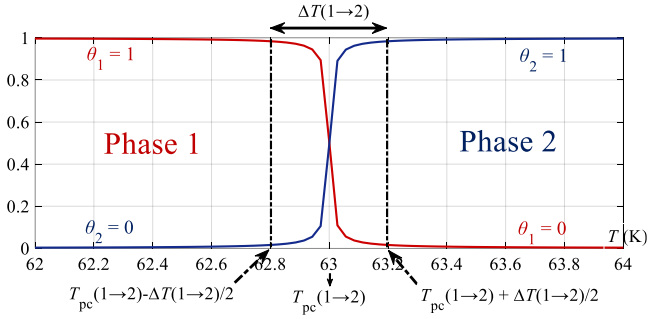

Fig. 2. Smoothed transition functions θ_1 and θ_2 between phase 1 and phase 2.

capacitors has been developed according to the geometry of our system and used to solve the heat diffusion equation [6]:

$$\rho C_p \frac{dT}{dt} = P_v + \mathrm{div}\left(k \cdot \overrightarrow{\mathrm{grad}}\, T\right) \tag{1}$$

where ρ is the density, C_p the heat capacity, P_v the power per unit of volume and k the thermal conductivity.

B. Phase change

In this study, the thermal properties of the nitrogen, i.e. C_p, and k, and the cryocooler power are functions of the temperature. However, a constant density ρ is defined for both liquid and solid phase.

To account for phase change, we solve the thermal equation after specifying the properties of a phase change material based on the apparent heat capacity formulation. The principle here is to add the latent heat L to the energy balance equation exactly when the material reaches its phase change temperature T_{pc}. It is assumed that the transformation takes place in a temperature range ΔT around T_{pc} as shown in Fig. 2. In this interval, the phase of the material is modelled by a smoothed function, θ, representing the phase fraction before the transition, which is equal to 1 before $T_{pc} - \Delta T/2$ and 0 after $T_{pc} + \Delta T/2$. The specific enthalpy, H, is expressed by:

$$H = \theta H_{ph1} + (1-\theta) H_{ph2} \tag{2}$$

wherein the indices "ph1" and "ph2" indicate the phases, respectively solid and liquid. By differentiating with respect to temperature, the equality (2) gives the following formula for the specific heat capacity:

$$C_p = \left(\theta_1 C_{p,\,ph1} + \theta_2 C_{p,\,ph2}\right) + \left(H_{ph2} - H_{ph1}\right)\frac{d\beta_m}{dT} \tag{3}$$

where β_m is the mass fraction here equal to:

$$\beta_m = \frac{1}{2}\left(\theta_2 - \theta_1\right) \tag{4}$$

since a constant density ρ is assumed in both phases.

In the perfect case, when $1-\theta$ is the Heaviside function, i.e. equal to 0 before T_{pc} and 1 after T_{pc}, $d\beta_m / dT$ is the Dirac pulse. Finaly, the effective thermal conductivity reduces to:

$$k = \theta_1 k_{ph1} + \theta_2 k_{ph2} \tag{5}$$

IV. Results and Discussion

We compared the two models, HCF and FEM, for 50 L of nitrogen in a bath of 300 mm in radius and 200 mm in height.

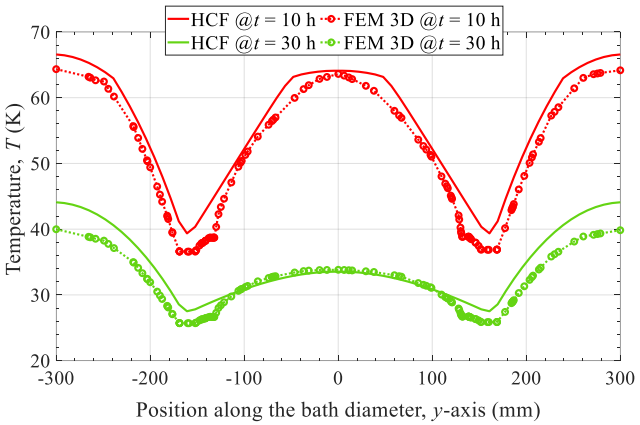

Fig. 3. Comparison of the nitrogen temperature distribution over the bath diameter after 10h and 30h of cooling.

In Fig. 3, the temperature at each location in the bath is plotted after different cooling times. The results of both methods are almost identical. The differences are probably caused by our assumption not to take into consideration the variation of the bath temperature in the azimuthal and longitudinal direction. The simulation time of the Heat Capacity Formulation (HCF) method is about 30 minutes, which is 10 times faster than the 3D Finite Element Method (FEM). As shown in Fig. 3, after 10 hours of cooling a temperature difference of about 30 K is observed between the exchanger and the center of the bath. However, after 30 hours of cooling this difference decreases to 10 K with a central bath temperature of 34 K.

In the final paper, all assumptions used in both models will be clearly detailed and discussed. We will also show how the system has been optimized through the temperature distributions of the different parts of the system. The influence of the liquid nitrogen bath volume on the cooling time will also be shown.

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