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Design Considerations of Cryogenic Cooling System for High Field Magnets

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Abstract**-- Several crucial issues are discussed in the design of cryogenic cooling system for high field magnets. This study is mainly motivated by our ongoing program to develop a 21 T Fourier Transform Ion Cyclotron Resonance Mass Spectrometer (FT-ICR MS). The magnets of this system will be built horizontally to accomplish the requirement of user friendliness and reliability, and the replenishment of cryogen will not be necessary by a closed-loop cooling concept. The initial cool-down and safety are basically considered in this paper. The effects of the helium II volume and the gap distance of the weight load relief valve (or safety valve) on the cool-down time and temperature rising during an off-normal state are discussed. The total amount of cryogenic cooling loads and the required helium flow rate during cool-down are also estimated by a relevant heat transfer analysis. The temperatures of cryogen-free radiation shield are finally determined from the refrigeration power of a cryocooler and the total cryogenic loads.**

1. INTRODUCTION

The high field magnets are critical components of instruments used in several research areas, such as biology, chemistry, physics, and material science. Several types of high field magnets especially for the Nuclear Magnetic Resonance (NMR) have been constructed to date and successfully operated [1-3]. While NMR magnet systems are oriented vertically, the Fourier Transform Ion Cyclotron Resonance Mass Spectrometer (FT-ICR MS) requires that the axis of the magnet should be oriented horizontally [4]. The development of horizontal magnet system including cryogenic cooling system, therefore, is another challenge for the high magnetic field science.

The development of a 21 T FT-ICR magnet system has been initiated by the international collaborative research program between the Korea Basic Science Institute (KBSI) and National High Magnetic Field Laboratory (NHMFL). The objective of this program is the design of compact and efficient magnet system, operating 1.8 K. As a first step, we have proposed a general concept of cryogenic cooling system [5]. In this paper, we discuss the several crucial issues which are possibly occurred in the cryogenic design process for high field magnets. Together with the initial cool-down, safety during an off-normal state is considered in terms of cryogenic point of view. While these crucial issues are considered here for a specific magnet system in this study, the presented results should be applicable to any high field magnet system, such as NMR or Magnetic Resonance Imaging (MRI).

2. CRYOGENIC COOLING SYSTEM

The cross-sectional view of cryogenic cooling system for a 21 T FT-ICR magnet to be considered here is shown in Fig. 1 The low temperature suprconducting coils are immersed in a bath of subcooled, 1.8 K superfluid helium at 1 atmosphere, which is connected to the 4.2 K helium reservoir through a narrow weight load relief valve (WLR V) which is used for safety. The saturated liquid helium is cooled by a Joule-Thomson (JT) heat exchanger and flows through JT valve, isentalpically dropping its pressure to around 1.6 kPa, corresponding saturation temperature of 1.8 K as it enters the helium II heat exchanger (or evapora-tor).

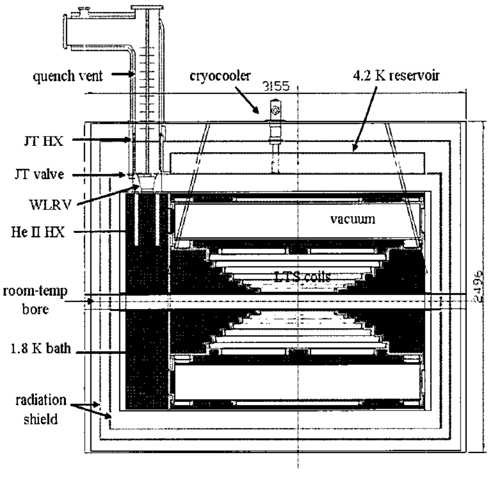

Fig. 1. Cross sectional view of cryogenic cooling system for 21 T superconducting magnets.

The helium leaves the He II heat exchanger as vapour, passing through the JT heat exchanger. The helium vapour leaves the cryostat and goes into a vacuum pump located outside of cryostat. The helium is then purified and liquefied by a two-stage cryocooler, and stored in the 4.2 K helium reservoir maintained a certain liquid level as shown in Fig. 2 A two-stage cryocooler is mounted directly on the cryostat where the magnetic field is less than 500 Gauss [4] and provides the cooling to the radiation shield and a 4.2 K helium reservoir.

In order to be an efficient system, the potential cooling power of the helium gas from the JT refrigerator will be used for pre-cooling [6] of the purified helium gas by two counter-flow heat exchangers located that one is between the purifier and the first-stage of cryocooler and the other is between the first-stage and second-stage of cryocooler.

The quench vent with a WLRV is located on the top of the helium II vessel and the high pressure helium is passing away through the quench vent during the off-normal state. To make a compact and efficient cooling system the finned-tube wound around the quench vent, so called the Hampson-type [7] heat exchanger, is employed as JT heat exchanger in the cryogenic system for 21 T superconducting magnets.

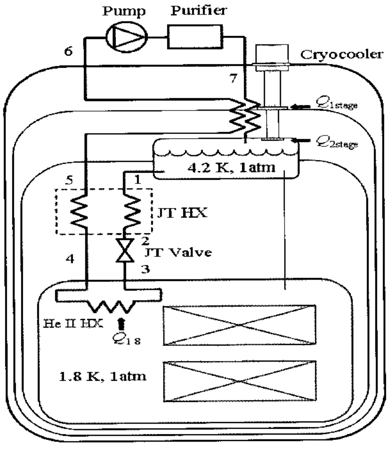

Fig. 2. Schematic of cryogenic cooling system for 21 T FT-ICR magnets.

3. CRYOGENIC COOLING LOADS

In the cryogenic system for 21 T superconducting magnets shown in Fig. 1, the cryogenic cooling requirements are continuously generated by four different physical mechanisms; thermal conducting through mechanical supports (Q_k), thermal radiation (Q_r), heat through current leads (Q_l), and heat leak through the WLRV (Q_{sl}). Among these loads, heat leak through the WLRV, so called superfluid heat leak, is a dominant cooling load on the magnet bath [8]. The amount of superfluid heat leak depends upon the gap of the valve and is well predicted by Mardion's model [9]. Experimental results have also verified this model [10].

The total heat load on the superconducting magnet bath ($Q_{1.8}$) is determined from (1) and should be balanced with the cooling capacity produced by JT refrigeration.

$$Q_{1.8} = Q_k + Q_r + Q_l + Q_{sl} \tag{1}$$

Using the first law of thermodynamics, mass flow rate through helium II heat exchanger is determined as

$$\dot{m} = \frac{Q_{1.8}}{h_{out} - h_{in}} \tag{2}$$

where h denotes the enthalpy and subscript *in* and *out* indicated the position at inlet and outlet of the He II heat exchanger.

During cool-down process by JT refrigerator from saturated helium (4.2 K) to superfluid helium (1.8 K), the total heat loads on the superconducting magnet bath is determined as

$$Q_{1.8} = Q_k + Q_r + Q_{sl} + \left(mC_p \frac{\Delta T}{\Delta t}\right)_{coil} + \left(mC_p \frac{\Delta T}{\Delta t}\right)_{He} \tag{3}$$

where m and C_p denote mass and specific heat, respectively.

4. RESULTS AND DISCUSSIONS

Fig. 3 shows the required cooling power to cool liquid helium down to 1.8 K by JT refrigeration system. The superfluid heat leak in this calculation is 0.217 W when the gap distance in the WLRV is 20 microns. Since the shape and dimension including the weight of magnets have been designed in order to satisfy the magnetic field requirement, the volume of helium II is the main parameter to determine cool-down time and required cooling power. The required cooling capacity as well as cool-down time increases with volume of liquid helium II. The required cooling capacity is 3.3 W when the volume of liquid helium II is 2000 liters and the elapsed cool-down time is 2 weeks. The mass flow rate through JT system is determined from (2). As same as required cooling capacity the mass flow rate increases with the volume of helium II. The mass flow rate of 0.19 g/s is required to cool liquid helium down to 1.8 K within 2 weeks.

The superfluid heat leak through WLRV is a dominant heat load at steady state. Fig. 4 shows the required cooling power versus the gap distance of WLRV under normal operation. The superfluid heat leak is estimated by Mardion's model for the gap distance between 20 and 140 microns. As the gap distance increases the required cooling capacity increases and varies between 0.25-1.55 W for a given gap distance. By purifying the magnet vessel before cooling the cryostat, the gap distance of the WLRV can be reduced approximately to 20 microns [8].

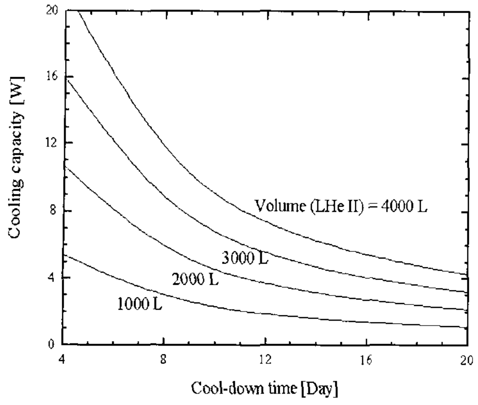

Fig. 3. Required cooling power of JT refrigerator during cool-down from 4.2 K to 1.8 K.

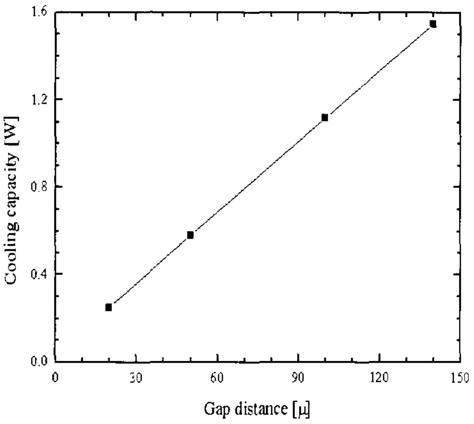

Fig. 4. Required cooling power versus gap distance of WLRV during normal operation.

Fig. 5 shows the elapsed time when the bath temperature of magnet rises from 1.8 K to 2.0 K during the off-normal state. The elapsed time increases with the volume of liquid helium II for a given gap distance. Since the superfluid heat leak increases with the gap distance, the elapsed time increases as the gap distance decreases for a given volume of helium II. As mentioned earlier, as the volume of He II increases the required cooling power as well as cool-down time increases. However, once the magnets bath cooled down, the elapsed time of temperature rising could be longer as the volume of He II increases. The volume of He II, therefore, has trade-off between in terms of the thermal and safety point of view. When the volume of He II is 2000 liters and the gap distance is 20 microns, it would take approximately six days for the temperature of magnets bath to rise from 1.8 K to 2.0 K. In order to maintain temperature rise to acceptable level and safe superconducting operational margins, three days hold-time is required [11]. During three days the temperature of magnets bath would rise 0.1 K when the gap distance of WLRV is 20 microns.

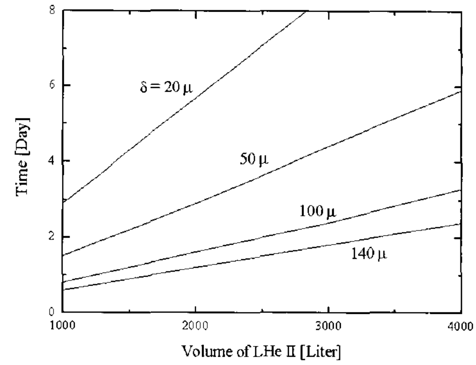

Fig. 5. Elapsed time of temperature rising form 1.8 K to 2.0 K during off-normal state.

Table 1 shows the estimated cryogenic loads in a 21 T FT-ICR magnet system. The details of cryostat support concepts are described elsewhere [12]. We have selected Haynes alloy [13] for support material, taking into account of effort, cost, and reliability. In order to compensate for imperfections in materials, flaws in assembly, and material degradation, we take 2 as the safety factor in the estimation of support conduction [14]. For thermal radiation, 50, 30, and 30 layers of MLI are used for the first, second stage radiation shield and He II bath, respectively. The reasonable value of the gap distance in the WRLV, 20 microns, is chosen according to the previous researches [8], [15]. The total cryogenic cooling loads at each stage are 65.85 W for first-stage and 1.01 W for second-stage. A two-stage pulse tube cryocooler PT415 [16] will be used for our cryogenic system and its refrigeration capacity is plotted in Fig. 6 [17]. Based upon the total cryogenic loads at each stage and the refrigeration capacity of cryocooler, the temperatures at each stage of cryocooler are determined, which are 52 K for first-stage cold head and 4 K for second-stage cold head. The intermediate radiation shield is thermally anchored to the first-stage cold head of cryocooler and the temperature of radiation shield at thermal connection is 52 K with temperature gradient of 2-3 K along the circumferential direction.

TABLE I
ESTIMATED CRYOGENIC COOLING LOADS OF 21 T FT-ICR MAGNET SYSTEM.

Temperature	1^{st} stage (52 K)	4.2 K	1.8 K
Conduction	7.67	0.74	1.82E-2
Radiation	32.69	0.21	1.37E-6
Current Leads	24.4	~ 0	~ 0
Superfluid Leak	n/a	n/a	0.217
Instrumentation	1.09	0.06	0.01
TOTAL [W]	65.85	1.01	0.245
Available Cryocooler Refrigeration Capacity [W] (Cryomech PT415)	80 W @ 65K	1.5	n/a

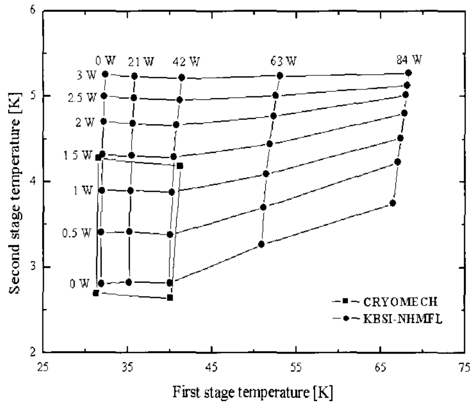

Fig. 6. Measured refrigeration capacity of Cryomech PT415 compared with manufacturer's data.

5. CONCLUSIONS

The crucial issues possibly occurring in the cryogenic design process for high field magnets have been successfully discussed. The volume of helium II and the gap distance of the weight load relief valve effect on the initial cool-down time and the temperature rising of helium vessel during the off-normal state. Also, the volume of helium II has trade-off between in terms of the thermal and safety point of view. Based upon the considerations of the crucial issues, the design of cryogenic cooling system for 21 T FT-ICR magnets will be completed. An integrated power and cryogenic cooling demonstration will be performed in the near future.

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