Mobile refrigeration system for precool and warm up of superconducting magnets

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Abstract. Conservation of helium has become more important in recent years due to global shortages in supply. Magnetic resonance imaging (MRI) superconducting magnets use approximately 20% of the world’s helium reserves in liquid form to cool down and maintain operating temperatures at 4 K. This paper describes a mobile cryogenic refrigeration system, which has been developed by Sumitomo (SHI) Cryogenics of America, Inc. to conserve helium by shipping MRI magnets warm and cooling them down or servicing them on site at a medical facility.

The system can cool a typical magnet from room temperature to below 40K in less than a week. The system consists of four single stage Displex®-type Gifford-McMahon (GM) expanders in a cryostat with heat exchangers integrated on the cold ends that cool the helium gas, which is circulated in a closed-loop system through the magnet by a cryogenic fan. The system is configured with heaters on the heat exchangers to effectively warm up a magnet. The system includes a scroll vacuum pump, which is used to evacuate the helium circuit with or without the magnet and turbo pump to evacuate the cryostat. Vacuum-jacketed transfer lines connect the cryostat to the magnet. The system is designed with its own controller for continuous operation of precool, warm up and evacuation processes with automatic and manual controls. The cryostat, pumps and gas controls are mounted on a dewar cart. One compressor and the system controller are mounted on a compressor and control cart, and the other three compressors are mounted on separate carts.

Keywords: MRI, Sumitomo, Cryogenics, GM, Expander, Cryogenic fan

1. Introduction
The mobile cryogenic system enables MRI and other superconducting magnets to be shipped warm, which saves money because they don’t have to be shipped by air, and conserves helium because it avoids boil-off losses when a magnet is shipped cold. It also conserves helium by minimizing the amount needed to cool it to 4 K. The modules of the mobile cryogenic refrigeration system are on carts that can be wheeled to an imaging suite in a hospital or they can be used at a central distribution center to cool down magnets that are then trucked to hospitals in the region. This system is also configured with heaters to warm up a cold superconducting magnet during servicing at a hospital or medical facility and use the same system to cool it down, which reduces the complexity relative to current processes.

The problem of cooling a mass down to cryogenic temperatures is different from the problem of removing heat from a mass that is already cold and is subject to heat loads from conduction, radiation, and internal heat generation. The present system is designed to minimize cool down time. Reference [1] describes a system that minimizes cool down time by utilizing the maximum output of the compressor, which is supplying gas to either a Brayton or a GM cycle expander. This is done by operating the expander at a high speed when it is warm, then reducing the speed, and by maintaining the optimum high and low pressures, as it cools down. A Brayton cycle expander has an advantage when gas is to be circulated to a remote load at a pressure near the high and/or low pressure of the compressor, typically 2.2/0.8 MPa gauge, because gas can be circulated before and/or after flowing through the expander, a cryogenic fan is not needed. The present system is designed to pre-cool or warm up a magnet in a cryostat that has a pressure limitation of about 0.2 MPa gauge. For this low pressure it is most practical
to use an expander operating at the higher pressures and have a fan circulate a separate, low pressure stream of helium through the cold end of the expander and the load. In the present system a cryogenic fan is used; however, reference [2] describes how a fan at room temperature can be used. The modular nature of the present system allows it to be adapted to keep a system cold, like the experimental system in reference [3]. This consists of two single stage GM expanders in a cryostat with heat exchangers integrated on the cold ends that cool helium gas, which is circulated by a cryogenic fan in a closed loop system through a superconducting power transmission cable at 20 K. The GM expanders run at a fixed speed and have a peak efficiency at about 30 K.

2. System Description

The present system is shown in figure 1, a schematic of the main components, and figure 2, a schematic of the supporting components. The refrigerator cryostat houses four (4) Sumitomo CH-110LT expanders, a cryogenic fan, and bayonets for transferring cold gas to and from a magnet cryostat, or in this case, a test cryostat. Each expander is connected through flexible gas lines to its own Sumitomo F-70 compressor. The four expanders are divided into two pairs, circulating gas being split into two streams and flowing through each pair in series. The standard CH-110 expander is optimized for temperatures near 70 K while the low temperature (LT) version is optimized for temperatures near 30 K. The configuration of the present system with the LT expanders and the circulating fan in the return line does not cool down as fast as the standard expanders would, but is used because it cools to lower temperatures less than 40 K and thus requires less helium to cool to 4 K. Heaters on the cold end heat exchangers can be used to warm up a magnet and also for system self-performance tests.

![Figure 1](imageurl)  
*Figure 1. Schematic of the Mobile Refrigeration System connected to a test load*
Figure 2. Support components for Mobile Refrigeration System. (VG—vacuum gauge, CV—check valve, BD—burst disc, RV—relief valve, SV—Solenoid valve, BV—Ball valve, PR—pressure regulator, PT—pressure transducer. Pressures in kPa)

The supporting components, which are mounted on the same cart as the refrigerator cryostat, are shown schematically in figure 2. Two lines connect to the refrigerator cryostat, the first is a helium supply and vent line that connects to the helium circulating line returning from the magnet cryostat, the second connects to the vacuum space. The scroll pump with a displacement of 17.1 m$^3$/hr. is used with the turbo pump to evacuate the expander cryostat and alternately to evacuate the circulating gas circuit. The fully assembled mobile refrigeration system is shown in figure 3 and figure 4.

Figure 3. Dewar Cart Assembly
The system controller consists of control hardware with an industrial touch screen PC and custom software. It connects to the system components and sensors shown in figure 1 and figure 2 with interconnecting cable assemblies. The controller with control software is designed to control the cool down and warm up processes of a superconducting magnet from 300 K to less than 40 K and 4 to 300 K, respectively. It is also programmed for a self-performance test to check the status of the system. The controller is programmed to change or vary the expander speeds, circulator speeds, and heater power based on the temperature of the circulating gas. It is also programmed to evacuate the vacuum chamber to the required vacuum levels automatically, and to charge and evacuate the helium circuit with or without the transfer lines being connected to a magnet. The control software allows both manual and automatic processes/controls. The system has the capability of remote connectivity, magnet communication, data storage and extraction, security level access options, plotting, user changeable safety and automatic process parameter settings. The user interface of the control software, as shown in figure 5, represents a typical system schematic, which shows real time system and magnet information comprising temperatures, pressures, speeds, heater power and on/off indicators.

The diagram shows the control cart and compressor cart assembly, with labels for the controller with industrial PC and compressor F-70H.

**Figure 4.** Control Cart and Compressor Cart Assembly

**Figure 5.** Control software user interface
The vacuum-jacketed transfer lines are 4m long-jacketed bayonets to interface with mating bayonets installed in the magnet. Typically, an interface tool is made that receives the male bayonets in a horizontal orientation and has vertical tubes that plug into the access port of the magnet cryostat. The ID of the tubes is typically greater than 25 mm. The supply tube should direct the cold gas to the bottom of the magnet cryostat and the return tube takes gas from the top of the cryostat. Reversing the transfer lines when warming the magnet generally provides faster warm up.

3. Component Performance
The cooling capacity of a CH-110LT expander at speeds from 2 to 3 Hz is shown in figure 6. If one were to cool down at 2.0 Hz, gas would bypass from high to low pressure through an internal relief valve in the compressor until the expander temperature drops below about 90 K. The present unit is programmed to run at 3.2 Hz while cooling from room temperature to below 100 K, then dropping to 2.0 Hz. Some gas bypasses in the compressor while the temperature is above about 150 K.

The cryogenic fan operating at 18,000 rpm has a lift with no flow of about 325 m and a flow of about 78 m³/hr at no lift. When starting cool down at 300 K, the cryogenic fan can circulate 2.0 g/s of helium at 220 kPa absolute against a pressure drop of only about 1 kPa. The system is thus designed with relatively large tubing, e.g.: greater than 20 mm ID where the flow is split and greater than 30 mm ID through the lines to the magnet. As the system cools down, the gas density increases and the viscosity decreases, thus the circulation rate increases, but so does the heat of compression. The fan speed is thus reduced from 18,000 rpm to less than 9,000 rpm below 50 K. Circulating fan losses are about 25 W due to conduction and 10 W due to compression at 20 K. Losses in bayonets, transfer lines, etc., at 20 K are about 100 W.

4. Cool Down Tests
Tests on a number of systems have been run in the laboratory and on magnets at customer sites. Our test cryostat has 34 mm ID lines and the test results shown in figure 7 are at a pressure of 202 kPa. Test results are plotted as an overlay of the capacity of the four expanders and the cooling available at the test load for circulation rates of 2, 5, and 10 g/s of helium. Temperature T0 is a little higher than the temperature of the test load because of the heat loss in the return transfer line. Tests with a constant heat load vs. circulator speed show a small change in T0 over a wide range of speed, e.g.: +/- 2,000 rpm.
There is little difference between operating at 18,000 rpm down to 100 K then dropping to 9,000 rpm, and operating at 18,000 rpm down to 200 K then reducing the speed linearly to 9,000 rpm at 50 K. During this test the circulation rate increased from 3.4 g/s at 290 K to 10 g/s below 90 K.

**Figure 7.** Cooling at four expanders, Qce, and net cooling at a test load with helium circulation rates of 2, 5 and 10 g/s. The broad line shows the heat load applied in the test cryostat.

Figure 8 plots the temperatures and circulation rate for a magnet that took around four days to cool down, but the time is normalized. The location of the temperature sensors are shown in figure 1. These temperatures reflect the drop in temperature of the circulating gas as it returns from the magnet and flows through the two expander cold end heat exchangers. Pressure in the magnet was maintained at 220 kPa until the temperature reached 30 K, then the He supply valve was closed and the pressure dropped to 160 kPa when the magnet reached 22 K. The initial circulator speed was 18,000 rpm and the initial circulation rate was 3.2 g/s. The default cool down program increases the circulation flow rate during cool down; however, the user can control the flow rate to lower values as illustrated in figure 8.

**Figure 8.** System key temperatures and cryogenic fan flow rate during typical cool down of a magnet.
5. Warm Up Test
Warming up a magnet requires an interface tool on the magnet cryostat that the transfer lines plug into. Prior to inserting the transfer lines into the tool, they are capped and evacuated, then filled with He. A purge is maintained while they are plugged into the tool, with the supply gas going to the top of the magnet. Care is needed when starting the warm up to avoid a sudden vaporization of residual liquid that could rupture a burst disc. The cryogenic fan can be run at very low speeds and allows a very slow cooling of the circulating piping and a slow rise in pressure such that venting through valves SVa or RV140 (figure 2) is controlled. Each of the expanders has a 400 W, 240 VAC, 60 Hz heater on the cold end heat exchanger, thus the magnet can be warmed up faster than it can be cooled down. Tests similar to figure 9 have shown that the cryogenic fan speed and the heater settings allow the warm up rate to be controlled to avoid thermal stresses in the magnet.

![Graph showing temperature and heater power against time.](image)

**Figure 9:** Warm up system self-test

6. Conclusions
A mobile cryogenic system has been developed which has a cooling power of 1550 W at room temperature and has been demonstrated to cool MRI size magnets from 300 to 22 K in 4-7 days. The system has a total heater power of 1600 W at 240 V, 60 Hz, and can warm up the MRI size magnets in 3-4 days in a controlled way.

The mobile and modular nature of the system allows it to be adapted to different cooling and service applications. The present system is designed to cool down and warm up a magnet. Work is in progress on systems that are designed to maintain cooling at a fixed temperature for a long period of time.

7. References
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