Design of Cryogenic Heat Exchangers and associated Sub-Systems for Controlled Cool-down and Testing of Superconducting Magnets at FRIB

N. Hasan, V. Ganni, A. Fila, F. Casagrande

Facility for Rare Isotope Beams (FRIB), Michigan State University (MSU), East Lansing, MI 48824 USA

E-mail: hasann@frib.msu.edu

Abstract. The Facility for Rare Isotope Beams (FRIB) is a continuous wave heavy ion beam linear accelerator designed for a maximum beam energy of 400 kW and using in-flight (fragment) production and separation to generate rare isotope beams. Spatial separation of the isotopes is achieved by using superconducting magnets with a high magnetic field, large aperture, and iron-dominated core. There are a total of 14 superconducting magnets used in the fragment separator section of the facility. Designs for these magnets are relatively new, and it poses challenges in several aspects of the cryogenic design and operation such as, compact coil and cryostat design, thermal shield design, and a controlled cool-down to the operating temperature while avoiding high thermal stresses. Helically coiled finned-tube cryogenic heat exchanger designs are considered for the controlled cool-down of superconducting magnets with up to 22.4 tonnes of cold mass. These heat exchangers use liquid nitrogen cooled helium gas to cool the superconducting magnets. They demonstrate high thermal effectiveness and mechanical flexibility that are essential for the variable operating temperatures (300 – 4.5K) experienced during a cool-down process. This paper presents an overview of the process design, analysis, fabrication and operation of cool-down heat exchangers and their associated sub-systems developed at FRIB.

1. Introduction

The Facility for Rare Isotopes Beams (FRIB) at Michigan State University will use projectile fragmentation and induced in-flight fission of heavy-ion primary beams at energies of 200 MeV/u and higher and at a beam power of 400 kW to generate rare isotope beams [1, 2]. The heavy-ion beams will be accelerated in a superconducting -RF folded driver linear accelerator, consisting of 46 cryo-modules and 4 superconducting di-pole magnets [3]. The experimental system consists of 14 new superconducting magnets (di-poles and quadrupole triplets) in the target and fragment pre-separator section [4, 5]. The experimental system including these new superconducting magnets will interface with the legacy A1900 fragment separator superconducting magnets from the NSCL era [6]. However, the design and cryogenic requirements for these new magnets are significantly different from those used in the past (for the NSCL). The cool-down mass in these new magnets can be as high as 22.5 metric tonnes (approx. 2.0 GJ of cool-down energy, 300-4.5K) and the liquid helium storage during typical operation can be as high as 2000 liters (approx.) [7]. Also, some of these magnets (specifically the di-poles) have larger coils that prevent separate testing of the superconducting coils in a test dewar. Hence,
there is a need for development of cryogenic infrastructure for testing of these new superconducting magnets for FRIB experimental system.

In the past, cool-down with 4.5 K liquid helium has been used on relatively smaller magnet tests. However, this method is very energy intensive, difficult to control and poses a greater risk of damaging the magnet due to thermal stresses developed during the cool-down. Typically, a cool-down flow with approximately 50 K temperature differential (between the magnet and cooling flow) is preferable [8]. This tends to put far less thermal stresses on the magnet system during cool-down. However, a heat exchanger system with a steady temperature control is required. Requirements (physical sizing, cooling capacity etc.) for these heat exchangers may vary widely depending on the application, available cryogenics infrastructure, and utilities. In the present paper, two different liquid nitrogen (LN) assisted cool-down heat exchanger designs (based on the capacity requirement and portability) are discussed. Both systems have been designed, fabricated, and installed at FRIB for testing and commissioning of FRIB’s experimental system superconducting magnets. The cool-down data and associated analyses is also presented.

2. Requirements for Cool-Down Heat Exchangers

Figure 1. Simplified schematic diagram of the (a) portable cool-down heat exchanger, and (b) cool-down heat exchanger with refrigeration recovery.

Gaseous helium flow cooled with liquid nitrogen (LN) is considered for the superconducting magnet cool-down. This allows the magnet to be cooled approximately to 100 K, and the rest of the cool-down is performed using gaseous helium mixed with 4.5 K liquid helium. This process is effective both thermodynamically – as almost 90% of the magnet’s cool-down enthalpy is between 300-100 K; and from a thermal loading (stress) aspect – as the integral thermal contraction of the magnet material is approximately the same between 300-100K and 300-4.5K. Of course, additional infrastructure for the cool-down helium flow processing (e.g. compressor for flow recirculation, buffer storage and associated
piping etc.) is required. As mentioned in Sec. 1, two different designs of cool-down heat exchangers are considered. These designs are discussed below.

For smaller test facilities, where portability is required – a simple cool-down heat exchanger design is presented. A simplified schematic of this cool-down heat exchanger is shown in figure 1a. This design can provide cold helium (300-80 K) supply flow of up to 5.0 g/s (nominally at 3.0 bar). The heat exchanger assembly consists of a single pass coiled finned tube heat exchanger (extracts cooling from vapor nitrogen), LN boiler with coils, wire-fin mixing assembly (mixing of 300 K helium with 80 K helium to provide required cold flow for controlled cool-down) and associated control valves. The entire assembly is housed in an insulating vacuum shell. Process and mechanical design of this heat exchanger assembly is discussed in sections 3 and 4 respectively. For this design, there is a need for a vaporizer to warm-up the cool-down return flow to ambient temperatures (not shown in figure 1a).

For large-scale cryogenic facilities, where a dedicated cool-down system is required for series of magnets (or cryo-modules), associated cryogenic distribution – a cool-down heat exchanger design with refrigeration recovery is presented. Recovering the refrigeration from the cool-down return flow (which can be significant) aids in reducing utilities (LN). Simplified schematic of this cool-down heat exchanger is shown in figure 1b. This design can provide cold helium (300-80 K) supply flow of up to 20.0 g/s. The heat exchanger assembly consists of two multi-pass coiled finned tube heat exchangers - HX-1 and HX2. They extract the cooling from the vapor (boil-off) nitrogen, and the cool-down return flow respectively. There is also a LN boiler with coils, a wire-fin mixing assembly (mixing of three helium streams to provide required cold flow for controlled cool-down) and associated control valves. The entire assembly is housed in an insulating vacuum shell. Process and mechanical design of this heat exchanger assembly is discussed in sections 3 and 4 respectively.

3. Design and Analysis of Cool-Down Heat Exchangers

Design and construction process for a coiled finned-tube heat exchanger is extensively discussed in [9-11]. The heat transfer surface areas \( (A_{t,S} \text{; tube-side, and } A_{s,S} \text{; shell-side}) \) can be calculated following [12], and the tube-side and shell-side convective heat transfer coefficients \( (h_t \text{ and } h_s \) respectively) can be found following [12, 13]. Once these parameters are known, the net thermal rating \( (UA) \) of the heat exchanger is calculated using the following equation:

\[
(UA) = \frac{1}{2} \ln \left( \frac{d_o/d_i}{2\pi n_p h_t k_t} \right) + \frac{1}{2} \frac{d_0}{h_s A_{s,S}} \quad \ldots (3.1)
\]

Here, \( k_t \) is the thermal conductivity of the tube material (copper), and \( N_p \) is the number of parallel coiled finned tube passes. \( L_t \) is the effective length of the heat exchanger, \( d_o \) and \( d_i \) are the tube outside and inside diameters respectively.

The heat exchanger total NTU is calculated using \( NTU = UA/C_{\text{min}} \). Here, \( C_{\text{min}} \) is the minimum of the stream capacity \( (m_{\text{cp}}) \) of the heat exchanger fluid streams. The heat exchanger NTU per turn is calculated from \( NTU_t = NTU/N_{tt} \), where \( N_{tt} \) is the total number of turns. The heat exchanger effectiveness per turn is calculated using the following equation [9] –

\[
\varepsilon_t = \begin{cases} 
\frac{1}{C_r} \left[ 1 - e^{-C_r(1-e^{-NTU_t})} \right] & \text{when tube stream capacity is minimum.} \\
1 - e^{-\frac{1}{C_r} \left[ 1 - e^{-C_r NTU_t} \right]} & \text{when shell stream capacity is minimum.} 
\end{cases} \quad \ldots (3.2)
\]

Here, \( C_r = C_{\text{min}}/C_{\text{max}} \). For helically wound coiled finned-tube heat exchangers, the effectiveness correction factor, \( Y \) (for multiple tube passes) and the overall heat exchanger effectiveness, \( \varepsilon \) are given by [9, 10] –

\[
Y = \frac{1 - \varepsilon_t}{1 - C_r \varepsilon_t} \\
\varepsilon = \frac{1 - Y N_{tt}}{1 - C_r Y N_{tt}} \quad \ldots (3.3)
\]

Based on the calculated heat exchanger NTU and effectiveness, the unknown inlet / outlet temperatures can be found.
3.1. Portable cool-down heat exchanger

In this heat exchanger, cooling of the warm (300 K) helium stream is initially carried out by a smaller (effective length: approx. 30 in.; diameter: 6.0 in.) coiled finned tube heat exchanger. The heat exchanger consists of a single pass of coiled finned-tubes wrapped around a mandrel and enclosed with the shell. It is shown in figure 2a. The rest of the cooling (to 80 K) is carried out by coils submerged in a liquid nitrogen bath (LN boiler). This cold (80 K) helium stream is appropriately mixed with warm (300 K) helium to achieve the target cool-down helium. The cool-down heat exchanger system is fully automated (PLC controlled) for cool-down and warm-up of magnet and can control the cool-down with a given temperature differential or a specified temperature provided by the user. This simple heat exchanger assembly is shown in figure 2b. Since, the cooling from the return stream is not extracted, the minimum LN consumption (per g/s of cool-down helium flow at 80 K) is approximately 3.0 g/s.

3.2. Cool-down heat exchanger with refrigeration recovery

For large-scale cryogenic facilities, the cool-down flow requirements can be substantially higher, and wasting the cooling from the cool-down return stream can not be justified. Refrigeration recovery from the cool-down return stream has the potential to reduce the LN consumption significantly.

In this design, the helium flow through HX-2 (helium – helium heat exchanger, refer to figure 1b) is adjusted to control the warm end temperature of the cool-down return stream (to extract maximum cooling from that stream), the warm (300 K) helium stream flow rate is adjusted to attain the target cool-down temperature and the helium flow through HX-1 (nitrogen – helium heat exchanger, refer to figure 1b) is controlled to provide the overall required cooling flow. A process model for this cool-down heat exchanger system was developed and the helium flow fractions across the automatic valves were optimized for minimum LN consumption. For the given heat exchanger configuration, figure 3 shows the optimized LN usage, pre-cooled helium stream temperature to the LN boiler and cool-down return stream temperature at warm end of HX-2 as a function of the cool-down supply temperature. It is observed that, for a cool-down flow of 20.0 g/s the maximum LN consumption is approximately 30.0 g/s. For a cool-down supply temperature of approximately 140 K, cool-down return stream temperature is the lowest (approx. 230 K). This is due to the significantly higher flow imbalance between the two cross-counterflowing helium streams.
Figure 3. Optimized cool-down heat exchanger process parameters as a function of the cool-down supply temperature.

Figure 4. 3D model of the (a) cool-down heat exchanger cold box, (b) HX-1 and HX-2 assembly with section view, and (c) LN boiler assembly.
The mechanical design of this large-scale coiled finned-tube heat exchangers follow [11]. Both the coiled finned-tube heat exchanger (HX-1 and HX-2) constructions are fundamentally similar to the cool-down heat exchanger described in Sec. 3.1. However, multiple coiled finned-tube passes are used here. Moreover, HX-1 is nested inside HX-2 and the LN boiler is nested inside HX-2 mandrel. The coiled finned-tube heat exchangers, LN boiler and cryogenic piping is enclosed in a 28 NPS (approx. 0.7 m) shell. The entire cold box assembly is approx. 10.5 ft. (3.2 m) tall. The overall cool-down heat exchanger cold box, coiled-finned tube heat exchanger assembly and the LN boiler assembly is shown in figure 4.

4. Controlled Cool-Down of Superconducting Magnets at FRIB

The portable cool-down heat exchanger was installed and commissioned at FRIB SRF testing facility in July 2020. It was utilized for cool-down of the three (subsequent) cold iron quadrupole triplets (CIQT1, 2 and 3) preceding the magnet testing. These are the largest superconducting magnets by cold mass at FRIB Experimental Systems. They have a cool-down mass of approx. 22.5 metric tonnes (each), and the corresponding cool-down load (300 – 100 K) is 1871 MJ. The nominal liquid helium storage in each of these magnets is 2000 liters.

![Graph showing cool-down temperatures and flow rates](image_url)

**Figure 5.** Cool-down flow (measured) and temperatures (estimated and measured) during CIQT1 superconducting magnet cool-down at FRIB SRF testing facility using the portable cool-down heat exchanger.

CIQT1, CIQT2 and CIQT3 were cool-down and tested in July 2020, October 2020 and January 2020 respectively. Each of these processes took approx. 3 weeks for magnet clean-up, cool-down, fill and steady-state operation for magnet field mapping. The maximum cool-down flow from the portable heat exchanger was limited to approx. 4.5 g/s. This limitation is due to pressure drop in existing warm piping and allowable pressure in magnet during cool-down etc. The portable cool-down heat exchanger was used for cooling down the magnet from 300 K to 100 K. Then 4.5 K liquid helium mixed with warm (300 K) helium gas was used to cool magnet to 4.5 K. Figure 5 shows the transient (measured and estimated) cool-down temperatures with flow provided from the heat exchanger. The estimated cool-down time (300 – 120 K) with 5.0 g/s and 50 K temperature differential for CIQT is 16.5 days, while
the actual cool-down time (300 – 100 K) with variable flow (due to pressure drop during cool-down) and temperature differential (magnet link adjustment, instrumentation commissioning etc.) was about 17.8 days. The Calculated cool-down time (300 – 100 K) with actual cool-down flow and cool-down supply temperature shows very good agreement with measurements.

Figure 6 shows the transient (measured and estimated) cool-down temperatures with flow provided to superconducting dipole (SCD4) cool-down at FRIB Experimental System test station from the large-scale heat exchanger (with refrigeration recovery). This heat exchanger is part of the FRIB target and fragment separator cryogenic system. This system consists of a 175 m long cryogenic transfer line (6 process headers), 14 magnet distribution boxes including one for magnet test station [14]. This test station supports additional magnet testing. The SCD4 dipole has a cool-down mass of approx. 3.4 metric tonnes, and the design cool-down load (300 – 100 K) is approx. 325 MJ. The cool-down data presented in figure 6 started in early June 2021. It took approx. 4.5 days for magnet clean-up, cool-down, fill and steady-state operation for magnet field mapping. The cool-down flow used from the heat exchanger was variable due to pressure drop in warm piping, magnet and elevated back pressure on magnet. A constant cool-down supply temperature (adjusted by user as time progresses) was used instead of constant temperature differential to closely monitor and adjust magnet tension links. The actual cool-down time (300 – 100 K) was observed to be 84 hrs, and the calculated cool-down time (300 – 100 K) with actual cool-down flow and cool-down supply temperature shows fair agreement with measurements.

5. Summary and Conclusion
The design and implementation of two different types of LN assisted cool-down heat exchangers are discussed in this paper. These heat exchanger designs are developed considering variety of capacity
requirements, portability, energy / LN consumption, operating modes (cool-down and maintenance), and maximizing availability for the testing facility. The design, fabrication and assembly of these cool-down heat exchanger systems are carried out in-house at FRIB, with locally available heat exchanger elements (finned tubing). Preliminary cool-down process models were developed for these heat exchangers and the experimental system magnets, and they show fair to very good agreement with field measurements. A process model for the heat exchanger with refrigeration recovery have also been developed. Better characterization of the system and additional measurements (LN consumption) are required to validate this model. At present, more effort to characterize the loads (cryogenic transfer line, magnet systems) and the cool-down heat exchangers (both designs) is being undertaken.

6. References
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Acknowledgments
This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.