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Integrated remote cooling system using a GM cryocooler

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Abstract. Sumitomo (SHI) Cryogenics of America Inc. has developed a novel cryogenic cooling system integrating a remote cooling gas flow circuit with a Gifford-McMahon (GM) cold head to cool a remote load. This innovative approach eliminates the need for a separate gas flow circuit and circulator, leading to an efficient, compact, and cost-effective solution for various cryogenic applications. This system utilizes helium scroll compressors to supply gas to a GM cryocooler. A portion of the return gas flow from the cryocooler is then diverted into the remote cooling circuit, where it is first cooled by a counter-flow heat exchanger and further cooled by the cryocooler. This cooled gas is then delivered to the remote load through vacuum-jacketed lines before returning to the main system. The system is equipped with a vacuum pump and valves, allowing for independent maintenance and cleaning while ensuring seamless operation of the main refrigeration system. In this paper, we will discuss and present system configuration, cooling performance, and system losses.

1. Introduction

Recent innovations in superconducting magnet technology, particularly for MRI systems, have created magnets with significantly reduced helium mass and limited thermal contact areas. Central to these innovations is the use of hermetically sealed, closed helium volumes. [1,2]. However, these changes render traditional cooldown methods, such as the SHI Low Pressure Cooler[3,4], ineffective as they require an open gas circuit with large thermal contact areas. These legacy systems are also often large, complex and costly. Without a cooling system, it can take these magnets weeks to reach superconducting temperatures, posing challenges for both manufacturing and maintenance[5].

To reduce the cooldown times of these new magnet designs, a new generation of cooldown systems are required. To address these challenges, Sumitomo Heavy Industries (SHI) has developed the Rapid Cooling System-Recuperator.

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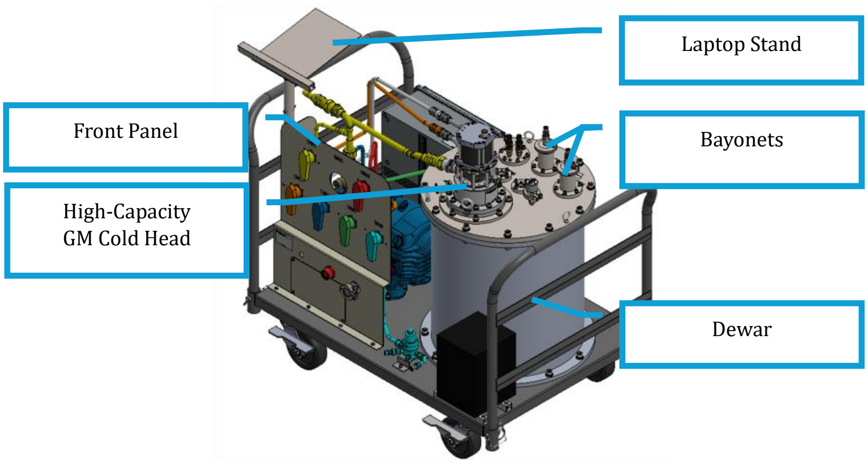

Figure 1. Model of the RCS-Recuperator proof-of-concept Dewar Cart.

2. Design

2.1 Overview and Operation

The Rapid Cooling System-Recuperator (RCS-Recuperator) is a novel cryogenic cooling system, integrating a gas circuit for remote cooling in series with a high-capacity Gifford-McMahon (GM) cold head[6]. This system is cost-effective, compact, and efficient. Integrating the cold head and remote cooling circuit in series, removes the need for an independent circulator, substantially reducing system cost and complexity. The cooling circuit is designed to operate between 0.6-0.8MPa to exploit the higher-pressure tolerances of modern superconducting magnets.

The RCS-Recuperator's proof-of-concept is composed of a single 30" x 42" dewar cart, as shown in **Figure 1**, that can be moved into position and connected by vacuum-jacketed lines to the remote target (such as a superconducting magnet). This operation can be handled by a single operator, through a space as narrow as a door. The system can then, be quickly connected together using Aeroquips and bayonets. After which, the remote circuit can be evacuated and filled before cold gas is supplied to the remote target.

2.2 Construction and Configuration

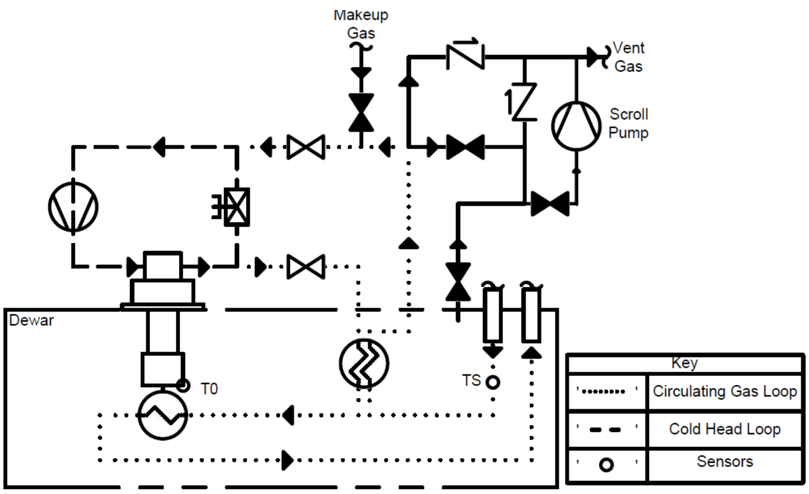

Figure 2. Piping and Instrumentation Diagram of the Rapid Cooling System-Recuperator.

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The RCS-Recuperator is composed of three connected sections: the crycooler, the remote cooling circuit, and the supporting functions. These are shown in **Figure 2.**

The cryocooler section is composed of a single high-capacity Gifford-McMahon cold head on the dewar cart connected to two SHI F-70H compressors via flexible hoses. The compressors operate in parallel, and their flow is combined in a manifold that additionally filters the gas for moisture. The return gas from the cold head flows through a flow control valve before returning to the compressors.

A portion of the gas leaving the cold head is directed into the circulating loop by the control valve. This gas flows into the system's dewar where it is initially cooled by the recuperator. The cooled gas then flows to the cold head where it reaches its lowest temperature. It continues to flow out from the system via a bayonet and vacuum-jacketed line before reaching and cooling the remote target. The gas flows back through the recuperator and is returned to the compressors.

The supporting functions section contains the hardware required to manage the gas pressure throughout the system. This includes a makeup gas connection, a common vent line, and a vacuum scroll pump. In addition to evacuating the remote circuit after connection and prior to use, the vacuum pump also evacuates the dewar vacuum.

3. Testing

3.1 Setup and Initial Results

The RCS-Recuperator proof-of-concept test setup can be seen in **Figure 3**. To investigate its performance, a Heat Load Simulator (HLS) consisting of an adjustable heater assembly in a vacuum space was constructed. The HLS was connected to the RCS-Recuperator using vacuum-

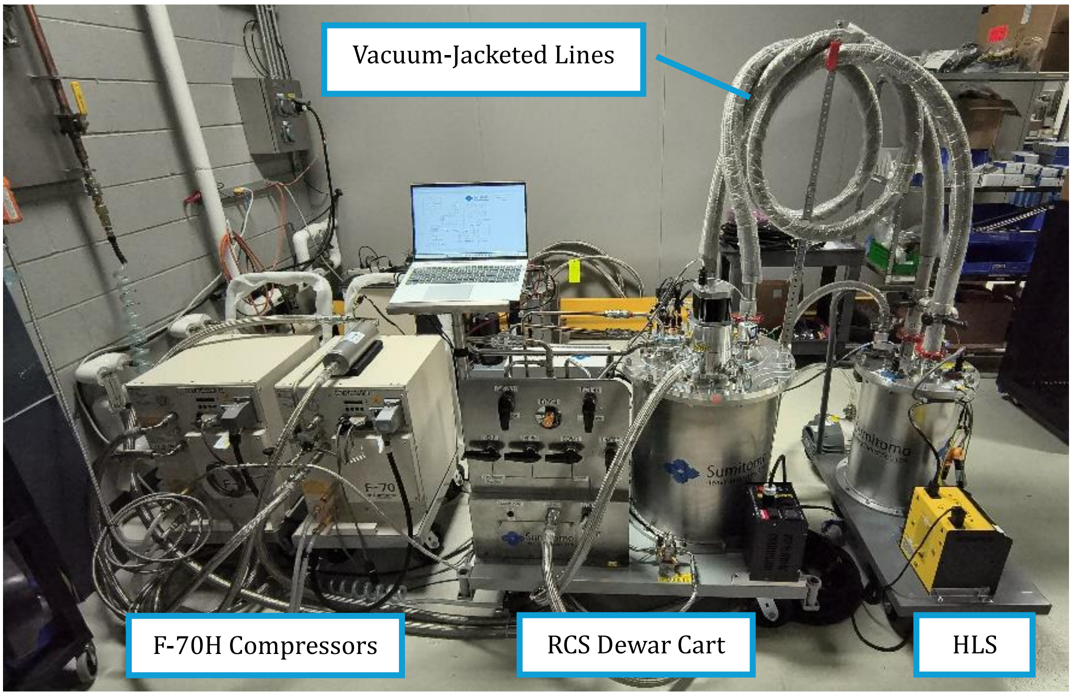

Figure 3. Test setup of the Rapid Cooling System-Recuperator proof-of-concept connected to the Heat Load Simulator.

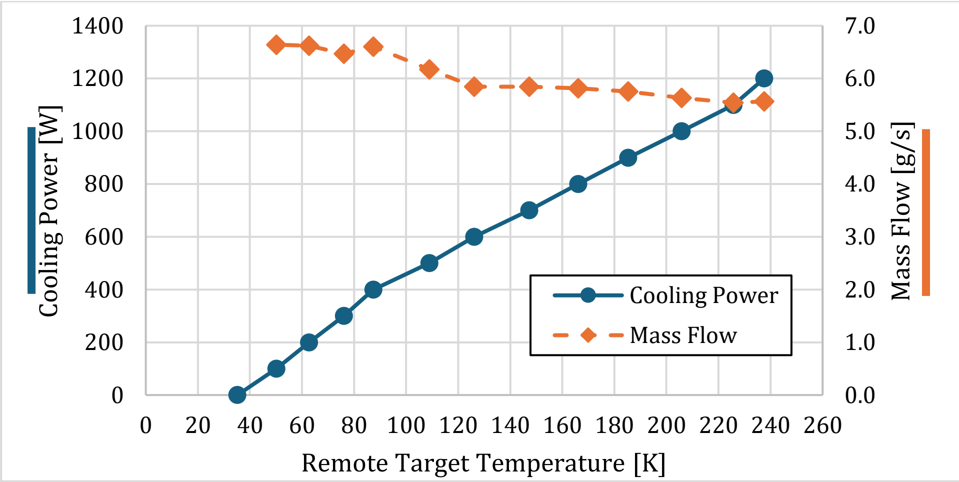

Figure 4. Performance curves for temperature and mass flow of the RCS-Recuperator when operated at 60Hz with its flow control valve at 2.5 Turns Open.

jacketed lines. Testing of the system was conducted at 60Hz input power, setting the operating frequency of the cold head to 2.4Hz. To reduce operational complexity, the flow control valve used to regulate the cooling circuit flow was maintained at a constant opening. Early experimentation identified the optimal position of this valve at 2.5 turns open. During cooldown, makeup gas was added to the system to maintain a target input pressure to the compressors at 0.65MPa.

Under these conditions the system was able to achieve 1200W of cooling power at 238K and a minimum temperature of 35.2K, see **Figure 4**. The circulating mass flow was seen to slowly rise from 5.6g/s as the gas properties changed with decreasing temperature. The mass flow shift below 100K was due to the full closing of relief valves internal to the system.

3.2 Estimated Magnet Cooldown

Figure 5 shows the estimated cooldown time of a 2000kg OFHC copper mass as cooled by the RCS-Recuperator. This predicts a cooldown time of 3.3 days to 77K and 8.5 days to 35K. This

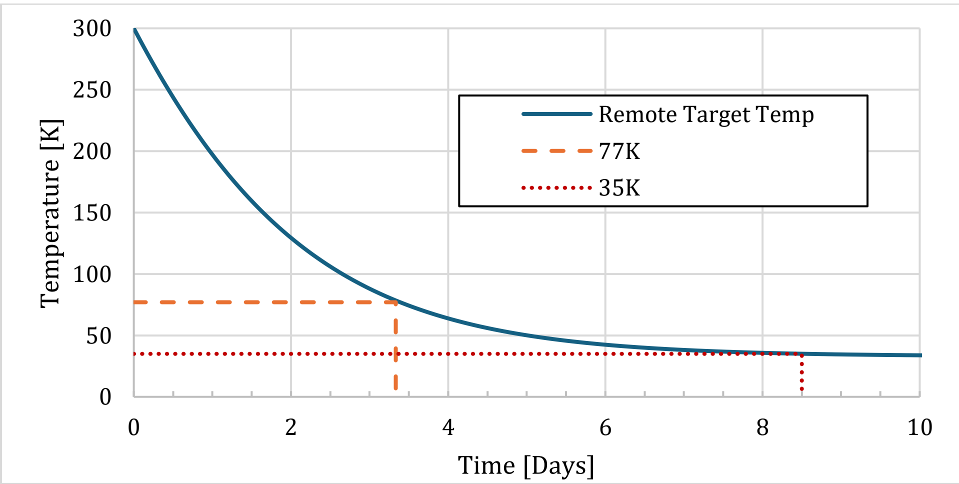

Figure 5. Cooldown estimate of a 2000kg OFHC Copper mass using the performance curve of **Fig 4.**

highlights the value of improving cooling power closer to ambient conditions in these systems, with the temperature reaching 60K, more than 90% of the ultimate temperature, in the first half of the cooldown process.

4. System Improvements

4.1 Operating Improvements

Continued experimentation yielded additional improvements to both the minimum achievable temperature, and the near ambient cooling power. These improvements can be seen in **Figure 6.**

The minimum temperature of the system was lowered from 35.2K to 31.6K, as seen with the dashed line. This nearly 4K improvement was achieved by adjusting the flow control valve to reduce the mass flow in the circulating loop from 5.6g/s to 2.6g/s. This mass flow reduction reduces both the flow dynamic losses and the recuperator's ineffectiveness loss, which is proportional to mass flow.

Next, the cooling power was improved at 238K from 1200W to 1400W. This was accomplished by increasing the operating frequency of the cold head from 2.4Hz to 3.2Hz. At warmer temperatures and lower frequencies, the cold head is not able to utilize all the gas mass directed into it. Increasing the operational speed allows more of the gas to be used and decreases the pressure drop across the cold head.

4.2 Hardware Improvements

With the success of the proof-of-concept, another generation of the system is planned. As with any engineering endeavour, multiple opportunities for improvement have been identified and will be pursued.

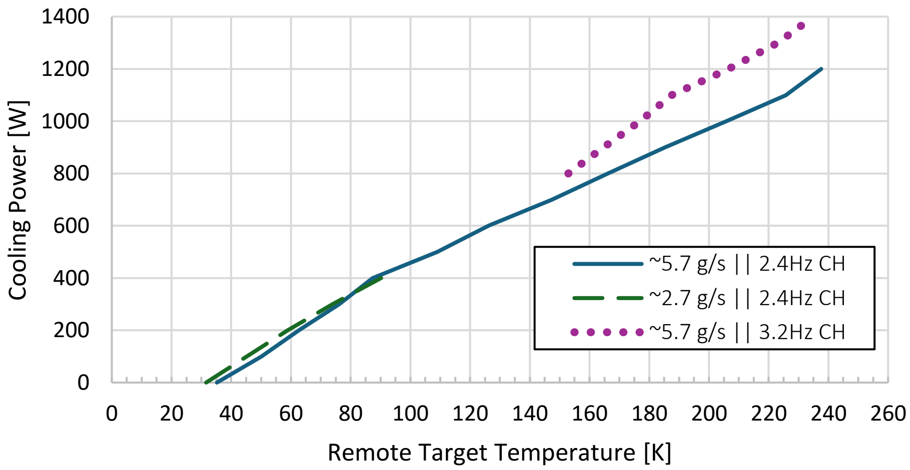

Figure 6. Performance curves for RCS-Recuperator under alternative test conditions. *Solid* – Performance curve of **Fig 4.** *Dash*– Improved minimum temperature. *Dot* – Improved near ambient cooling power.

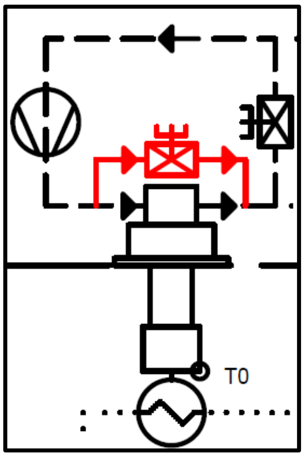

Figure 7. Piping and Instrumentation diagram, with gas bypass around cold head in red.

The first of these improvements is to replace the manually operated valves with remotely actuated valves. This is designed to further reduce both operator and system complexity. The valves will be controlled by the system's software, removing the operator from that process. Regarding construction, the piping will no longer need to be routed to the front panel, allowing a simplification of the system's layout and a potential reduction in total size. Additionally, system performance can be improved by allowing the program to dynamically adjust valves to the operating state.

The second, is to replace the cold head's synchronous motor with a stepper motor. This will allow the operating frequency of the system to be dynamically adjusted both above and below the 2.4Hz and 3.2Hz tested. By optimizing the cold head's frequency, the cooling power of the system can be improved depending on system state, as demonstrated by the 200W increase as 248K.

Finally, a gas flow bypass around the cold head is planned, as shown in **Figure 7**. Any gas that the cold head cannot use will be bypassed to the low-pressure side, further reducing system pressure drop and increasing mass flow to the circulating loop near ambient conditions. Furthermore, the RCS-Recuperator becomes capable of warming the remote target when the bypass is combined with a heating element in the circulating loop.

5. Conclusion

Sumitomo (SHI) Cryogenics of America Inc. has developed the Rapid Cooling System-Recuperator as a novel remote cooling system that combines a cryocooler and circulating loop in series. This removes the need for an additional circulating system, reducing system cost, and complexity. A proof-of-concept of the system demonstrated a minimum temperature of 31.6K and a cooling power of 1400W at 238K. The next iteration of the RCS-Recuperator is planned to add warm-up capabilities using a gas bypass, active control of the GM cryocooler frequency, and automated valves and system functions.

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