Cryogenic helium circulation cooling system with high capacity GM cryocooler

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Abstract. Sumitomo (SHI) Cryogenics of America Inc has investigated the capabilities of a circulating cooling system utilizing a High-Capacity Gifford-McMahon (GM) refrigerator and helium gas circulator for cooling a remote thermal load like a superconducting magnet. System cooling performance was investigated for circulation loop pressures of up to 2.0 MPa-g. The system comprises a Sumitomo CH-160 high-capacity refrigerator with integrated heat exchanger, off the shelf circulator, and bayonets housed in a cryostat, and vacuum jacketed transfer lines, vacuum pump, electrical & controls for system operation and testing. In this paper we present system configuration, cold head performance, input power, and net system cooling performance delivered to the remote thermal load. Cooling losses of the circulation loop associated with the cryostat, transfer lines, and circulator are mentioned.

1. Introduction

Many imaging and energy technologies utilize superconductivity. Cryogenic cooling is essential for the low temperatures required to operate all present-day superconducting materials. Applications can be broadly divided into low temperature superconducting (LTS) and high temperature (HTS) type. While LTS systems typically operate near 4 K and HTS systems operate in the 20-80 K range, both types benefit from refrigeration equipment which cools the application from a nearby platform. Such cryogenic cooling equipment can be configured to provide transitional cooldown and warm-up of the customer application, for example an MRI superconducting magnet. Alternately, the cooling system can be configured to provide continuous long-term refrigeration for periods of months or years.

A practical commercial refrigerant for LTS and HTS applications at present is pure helium, which is a finite natural resource sought by increasing worldwide strategic demand[1]. In the past, cryogenic cool-down was achieved with liquid nitrogen followed by liquid helium. Such practice is typically being updated with the use of stand-alone cooling systems, such as the mobile cryogenic system/low pressure cooler[2,3,4] from Sumitomo (SHI) Cryogenics. This platform produces cooling from four single-stage Gifford-McMahon (GM) cryocoolers using SHI model F-70 helium compressors. Helium is circulated by the cryogenic fan in the low-pressure cooler system in a separate closed loop at approximately 0.1 MPa-g to cool the superconducting magnet with no loss of helium.

Emerging designs for superconducting magnets have an increased proportion of solid content and a reduced volume of liquid cryogen compared to older magnets. This design shift reduces the

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internal heat transfer surface area for circulating cooling gas. This leads magnet designers to increase the pressure of the circulating cryogen to achieve practical heat transfer rates when pre-cooling. The increased circuit pressure provides useful cryogen mass flow in small diameter piping for low temperature and high temperature superconducting applications.

Sumitomo Cryogenics is developing convenient mobile cooling systems which use the recently launched large capacity pneumatic drive single stage GM cold head (CH-160). The Rapid Cooling System (RCS) prototype system with this cold head and cryogenic fan is designated as RCS – Circulator[5]. The RCS - Circulator is designed to deliver constant cooling with pressure up to 1.8 MPa-g. Testing of the RCS-circulator breadboard is the subject of this paper and is discussed in detail in the sections below.

2. Description of the test set up

The RCS-Circulator breadboard consists of a high-capacity CH-160 single stage GM cryocooler with an integral cold heat exchanger, cryogenic circulator fan, supply and return vacuum jacketed flex hoses, associated system sub-components, and heat load simulator (HLS).

The overall test arrangement is shown schematically in **Figure 1**. The system has two cryostat carts and two helium compressors are located on the floor nearby. The larger cryostat cart contains the RCS vacuum dewar, electrical control and data acquisition panel, user interface, scroll vacuum pump, manual valves, and helium supply and vent piping. The smaller cryostat cart contains the HLS. A pair of vacuum jacketed flexible hoses connect the two cryostats with mating bayonet fittings.

In the RCS dewar, the circulating helium enters at the return bayonet. It then flows into the heat exchanger in the copper heat station of the cold head, then into the cryogenic fan, out the

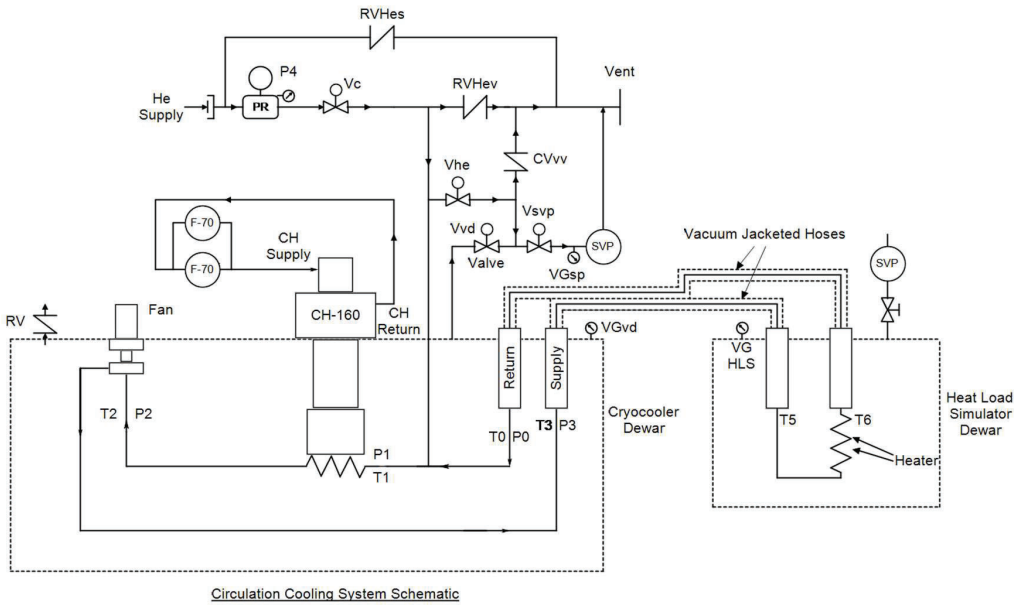

Figure 1. RCS – Circulator Breadboard Schematic.

supply bayonet, and through the vacuum jacketed supply hose. From there, it flows through the heater in the HLS dewar, then to the vacuum jacketed return flex hose, and back to the RCS dewar.

The RCS dewar contains the GM cryocooler, cryogenic centrifugal fan, piping, and female bayonet connections. The top plate assembly has pressure and temperature sensors. It also includes a relief valve and dewar vacuum gauge. A branch line is provided in the RCS top plate assembly between the return bayonet and the cold head heat exchanger for evacuating, charging, and venting the helium circulation loop. The 85mm diameter cryogenic fan is inverter – driven.

Two SHI model F-70H helium compressors are used in parallel to supply helium gas to the cold head. The F-70H compressors each require 460-480V, 60 Hz, 3 phase power with typical power consumption of 8.6 – 9.3 kW, or 380/400/415 V, 50 Hz, 3 phase power with typical power consumption of 7.3 – 7.8 kW. The compressors are water cooled.

The GM cryocooler is based on the SHI CH-160 cold head design. Its heat station contains an integral heat exchanger for the circulating helium gas. The cold head in the test can be operated at 2.0 or 2.4 cooling cycles per second (GM Hz).

Four manual ball valves in the external piping of the RCS dewar cart provide isolation of the dewar vacuum, the helium circulation loop, the helium supply, and the scroll vacuum pump inlet. The RCS dewar cart has a 6.3 mm (¼") Aeroquip connection port for the external helium supply to add make-up gas to maintain constant circulating pressure. Downstream of this port is a 3.1 MPa-g (450 psig) relief valve and adjustable single stage regulator with pressure sensor on the outlet. The regulator controls the minimum pressure available for the helium circulation loop. The loop is protected from overpressure by a relief valve set at 2.5 MPa-g (360 psig). A vacuum gauge is installed on the scroll vacuum pump. The pump outlet is piped together with two relief valve paths to an NW25 vent connection flange.

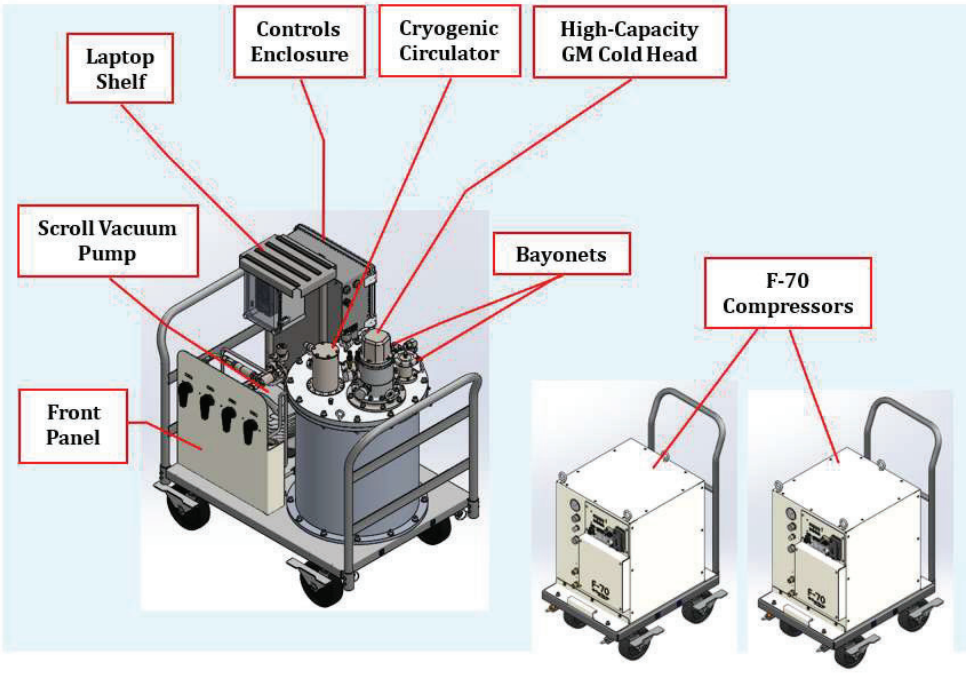

Figure 2. RCS-Circulator Components

The HLS dewar cart consists of the vacuum dewar with bayonet connections and internal heat exchanger assembly with heaters for the helium circulation loop. The dewar has a relief valve and vacuum gauge. The HLS cart also includes a variable AC transformer, power meter, and heater safety relay.

The LabVIEW-based user interface also acquires test data. The interface provides a system schematic displaying live parameter values and start/stop control of all powered components. It allows the user to select manual or automatic setpoint control for the cryogenic fan speed.

See **Figure 2** for the system components. See **Figure 3** for the test setup.

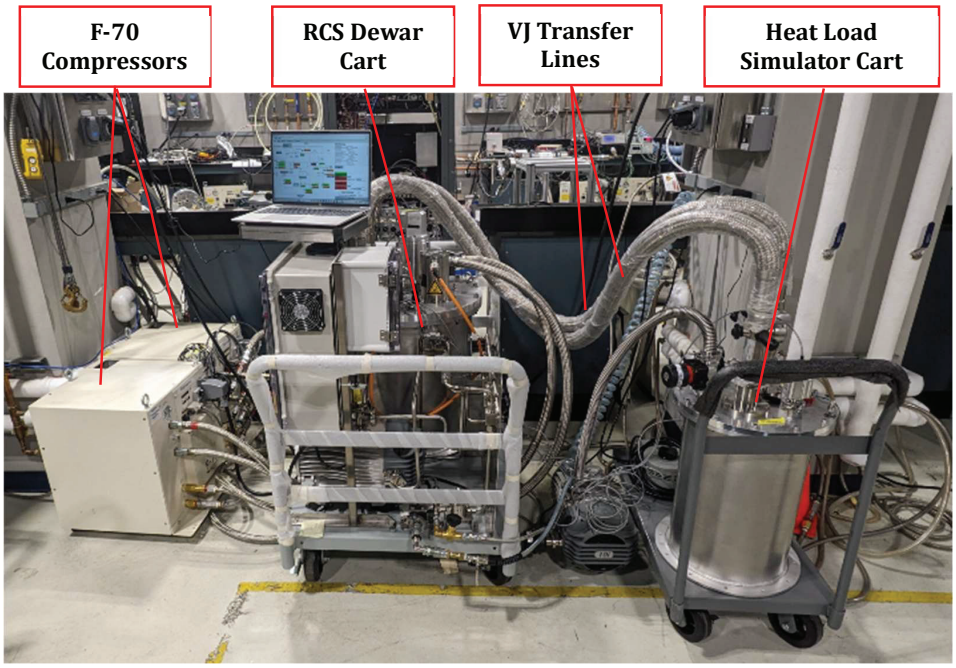

Figure 3. RCS – Circulator Breadboard Test Setup.

3. Testing

The system was primarily tested with the circulation loop at nominal pressure of 1.8 MPa-g. Initially there was no heat load applied in the heat load simulator. The temperature (T0) at the return bayonet was recorded for various fan speeds with 60 Hz compressors and 2.4 Hz cold head. Heat load was increased stepwise and for each heat load, the fan speed was varied to optimize, thus balancing available cooling power with fan compression losses. The resulting temperatures for testing at 400 W and 600 W are shown in **Figure 4**.

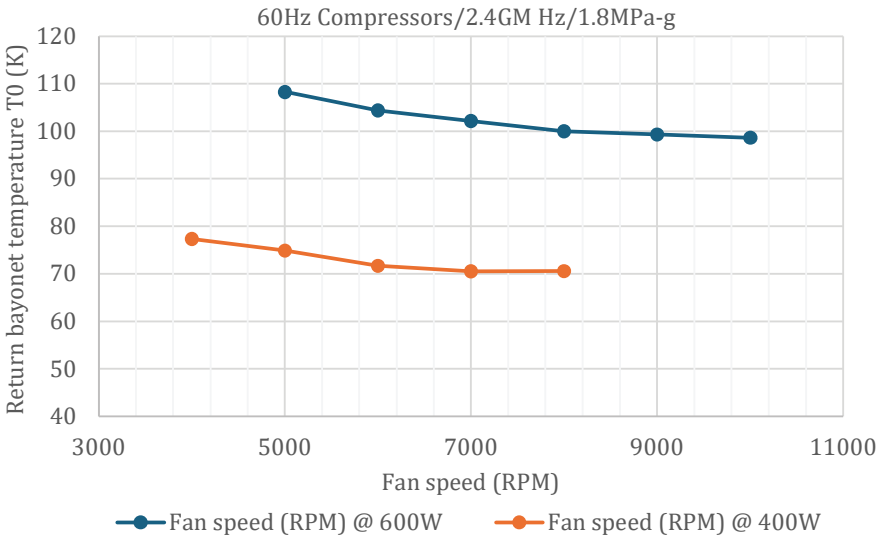

Figure 4. RCS – Circulator: Test Results for Varying Circulator RPM at Fixed Heat Loads

After further speed optimization tests, the fan speed setpoint control was configured to decrease linearly based on the return bayonet (T0) temperature. Fan speed is maximum 18,000 rpm when T0 is 200 K or greater and decreases linearly to minimum 5,000 rpm when T0 is 30 K or colder. Fan speed setpoint is shown with respect to the overall temperature range and cooling performance with 60 Hz compressors and 2.4 Hz cold head in **Figure 5**.

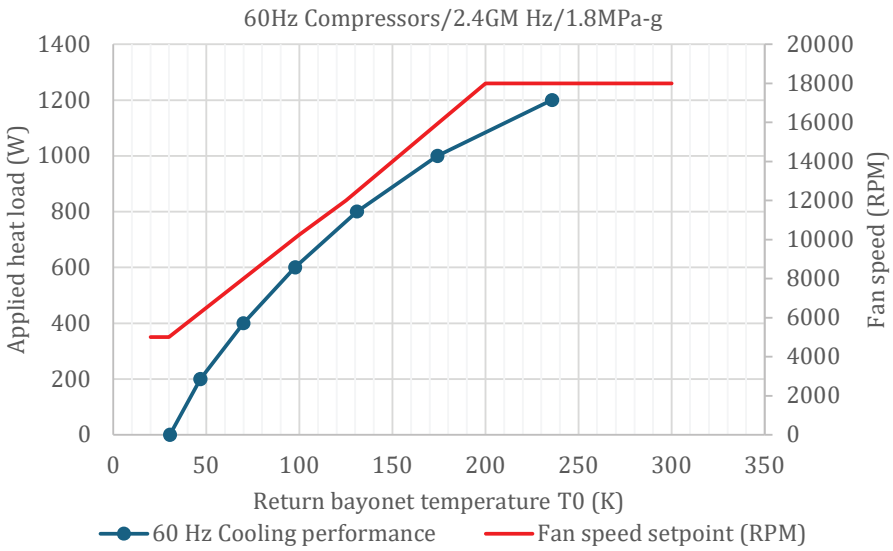

Figure 5. RCS –Circulator: RPM Setpoint Control and Baseline Cooling Performance

The circulator fan speed was controlled in this manner for subsequent tests. Baseline cooling performance with circulation pressure of 1.8 MPa-g is compared to that observed at 0.7 MPa-g, for 60 Hz compressors and 2.4 Hz cold head in **Figure 6**. The system achieved 1200 W at 236 K, 460 W at 77 K and 0 W at 30 K as minimum temperature for 1.8 MPa-g circulation pressure. The system achieved 800 W at 175 K, 400 W at 77 K, and 30 K as minimum temperature for 0.7 MPa-g circulation pressure.

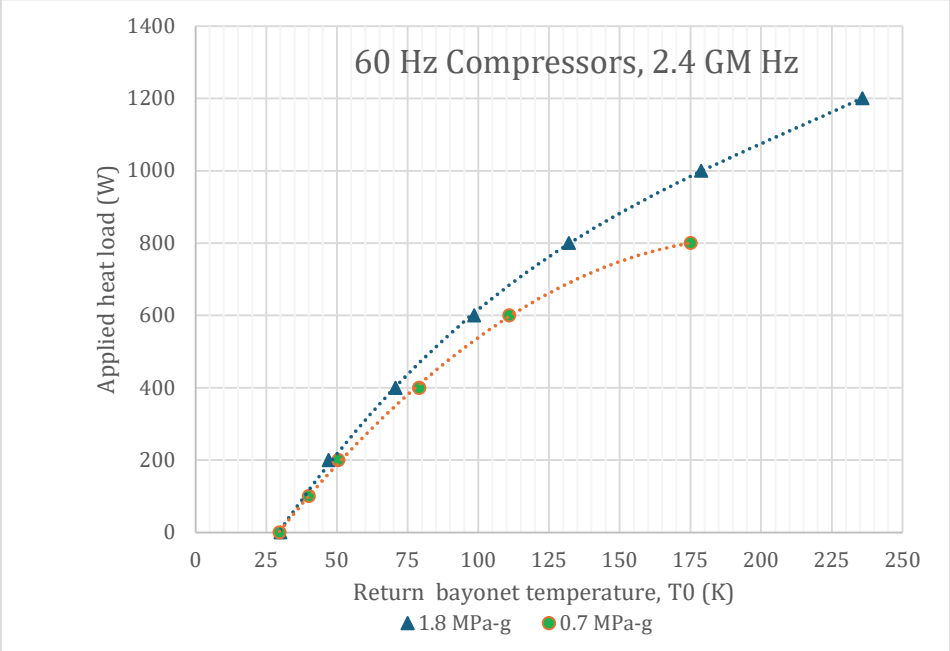

Figure 6. RCS –Circulator: Cooling Performance at 1.8 MPa-g and 0.7 MPa-g Circulation Pressure

Further testing has been conducted at 50 Hz compressor frequency and 2.0 Hz cold head. The system achieved 1050 W at 236 K, 400 W at 77 K, and 0W at 30 K at minimum temperature for 1.8 MPa-g circulation pressure. Cooling performance with 60 Hz compressors and 2.4 Hz cold head is compared to that with 50 Hz compressors and 2.0 Hz cold head for circulation pressure of 1.8 MPa-g in **Figure 7**.

The circulating helium mass flow was calculated from temperature and applied heat load readings at 1.8 MPa-g circulation pressure. As seen in **Figure 8**, the test demonstrated maximum helium mass flow at minimum heat load. With 60 Hz compressors and 2.4 Hz cold head, mass flow is at its lowest value of 6.5 g/s at the greatest temperature of 236 K. Density of the helium gas increases as its temperature decreases and mass flow is greatest (12 g/s) at minimum temperature of 30 K. With the fan speed of 5,000 rpm, cooling losses within the cryostat at 30 K are about 75 W.

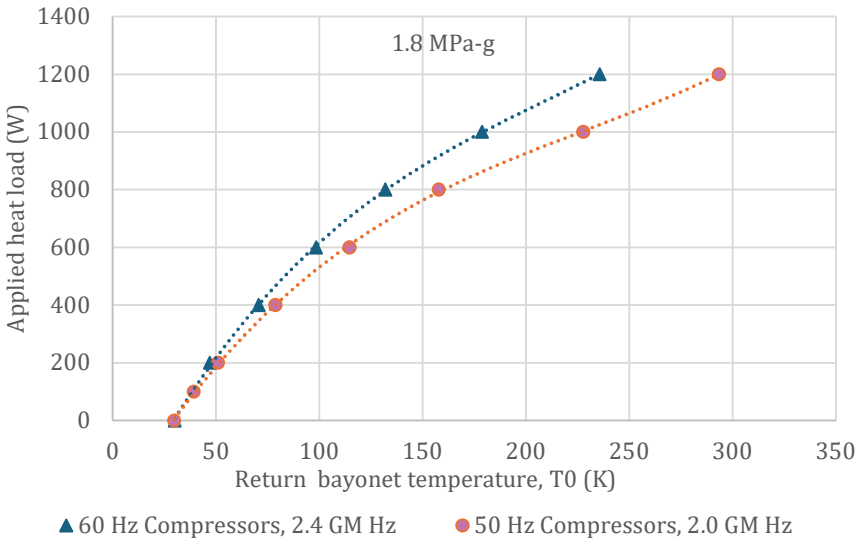

Figure 7. RCS –Circulator: 60 Hz Compressors, 2.4 Hz Cold Head and 50 Hz Compressors, 2.0 Hz Cold Head.

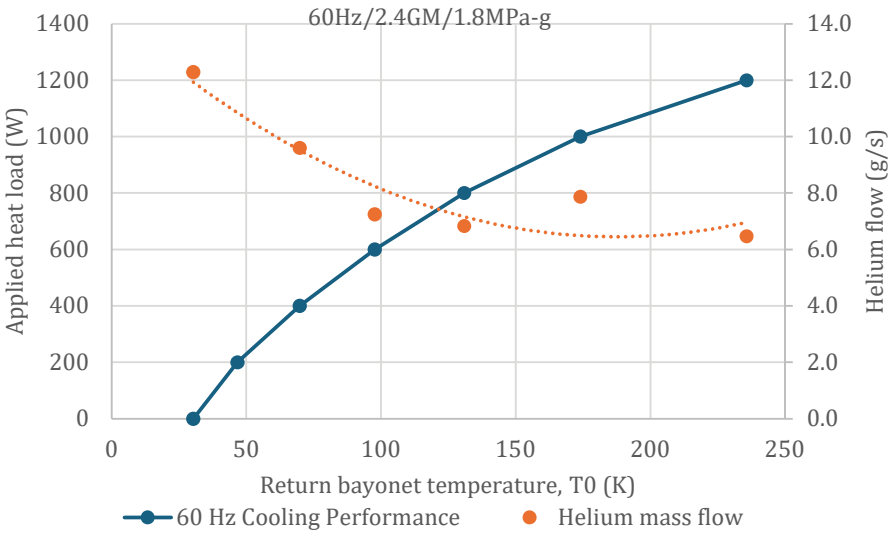

Figure 8. RCS –Circulator: Comp-60 Hz, CH2.4 Hz and Comp-50 Hz, CH2.0 Hz

4. Conclusion

Sumitomo (SHI) Cryogenics of America Inc has developed the RCS-Circulator prototype using a high-capacity GM cryocooler for high pressure applications. This system can operate with 0.7 MPa-g to 1.8 MPa-g circulating loop pressures. The system achieved 1200 W @ 236 K, 460 W @ 77 K at 1.8 MPa-g circulating pressure and normal operating speeds of compressor and cryocooler. By locating the circulator downstream from the cold head, the system produces useful cooling capacity for the application heat load.

Operating cryocoolers at higher speeds during cool down can further improve the system performance and system efficiency.

Acknowledgments

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