Cryogenic Thermal Studies on Cryocooler-Based Helium Circulation System for Gas Cooled Superconducting Power Devices

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ABSTRACT

Application of cryocoolers in cryogenic helium circulation systems suitable for cooling super-conducting power applications is presented. The design of a versatile cryogenic helium circulation system is presented. The relation between the various thermodynamic and fluid dynamic properties of the components and helium gas stream are studied to gain an understanding of the critical design challenges for effective systems. The importance of the design optimization was demonstrated using multiple cryocoolers and gas circulators in parallel and in series networks. The potential for application of cryogenic helium circulation systems is demonstrated by using one and achieving a small temperature gradient across a 30-m superconducting cable system that carried 5 kA.

INTRODUCTION

Electric power devices made of high temperature superconductors (HTS) have been of interest since the availability of the wire in long lengths [1-4]. Many prototype units of HTS power devices have been successfully demonstrated. Some devices have been integrated into electric power grids for long-term operational experience [5-9]. All the major demonstrations of HTS power devices have used liquid nitrogen as the cryogen in closed loop systems. One of the major challenges of propelling the superconducting power device technology for large-scale applications in electric power infrastructure is the complexity, capital costs, and regular maintenance needs of the cryogenic liquid nitrogen plants necessary for operation of any superconducting device. Some demonstration projects have opted for open cycle liquid nitrogen systems where liquid nitrogen reservoir tanks are replenished at regular intervals instead of on-site refrigeration equipment mainly to minimize upfront capital costs and maintenance needs [9]. Another challenge in bringing HTS power device technology to market place is the price of the superconducting wire. At the current market price of HTS wire of around $400 per kA-m, superconducting wire constitutes a major fraction of the cost of building any large device such as a superconducting cable, generator, motor, or transformer. To tackle the two challenges described above, simpler, low cost, and reliable cryogenic systems that allow operating temperatures lower than 77 K for superconducting power devices are essential. Lower operating temperatures allow for enhanced current densities in superconducting devices and thus lower the amount of required superconducting wire and associated capital expenditures. One option to simplify the cryogenic systems and expand the operating tem-

perature window for superconducting devices is to use a gaseous cryogen instead of using liquid nitrogen. Out of three potential gaseous cryogens (He, H_2, and Ne), helium is the common choice because of the operational hazard of H_2 and high cost of Ne. Additionally helium also offers the widest operating temperature window. One advantage of gaseous cryogens is that, unlike in the case of a liquid cryogen, higher temperature gradients can be tolerated across the superconducting device without having to deal with a phase change. This aspect is particularly important if multiple superconducting devices in an electric substation have to be cooled with a single stream of the gas or a long superconducting cable has to be cooled. Another advantage of gaseous helium is that its wider operating temperature window allows design flexibility for power devices to optimize them based on a given criteria such as lower capital cost, lower weight or smaller footprint, or certain power density [10]. These aspects are particularly important for designing superconducting power devices for space, aviation, naval, and automobile applications where weight and size reductions are important criteria. Another attractive feature of gaseous circulation is that in closed environments such as airplanes and ships that there is less asphyxiation hazard compared to using liquid cryogens in case of a system breach [11,12]. US Navy has successfully demonstrated the helium gas cooled high temperature superconducting degaussing system and propulsion motors [11-13]. For similar reasons indoor superconducting power applications such as cables for data centers are a potential near term application for gas cooled superconducting power systems.

To enable development of efficient cryogenic helium gas circulation systems large enough for superconducting power devices, the challenges involved in producing and circulating cold helium gas have to be understood. One method of producing cold helium gas is to use cryocoolers with attached heat exchangers through which helium gas is circulated with the help of high speed circulators [14]. Technical challenges involved in designing this kind of helium circulation system is to design and fabricate gas circulators that can produce large volume flow rates with a small heat leak into the cryogenic environment. Generally, the circulators can support only a small pressure drop (3-5 psi). Hence design of heat exchangers that can efficiently transfer heat from the gas stream to the cold head of the cryocooler is essential. Similarly, designing superconducting power systems with minimal pressure drop is also essential to successfully implement gaseous circulation as the means of providing cryogenic environment to the devices. The basic components of a cryogenic helium gas circulation system were described in a recent article on circulators [15].

The design of cryogenic helium gas circulation systems and the superconducting power devices to be cooled with helium gas circulation have to accommodate the limitations of helium gas as the cooling medium. Helium gas has lower specific heat capacity and lower dielectric strength compared to those of liquid nitrogen [14-16]. The superconducting devices have to be designed to minimize the heat load on the cryogenic system and a solid dielectric has to be selected to mitigate the two limitations listed above [16].

This paper describes the design of a versatile helium circulation system with two cryocoolers and three circulators. Experimental data are presented on volume and mass flow rates at variable circulator fan speeds, relations between the volume flow rate and mass flow rates, pressure drops, and temperature gradients. To present as an example of the capability and applications of the circulation system, the circulation system was connected to a 30-m long superconducting cable system to obtain experimental data on temperature gradients across the cable system at a range of mass flow rates. A brief description of a recent successful demonstration of a high temperature superconducting DC cable cooled by gaseous helium circulation is also presented.

EXPERIMENTAL SET UP

Helium Circulation System

A versatile cryogenic helium circulation system was designed to understand the relation among the components and the various design parameters of circulators, heat exchangers, and heat loads. Figure 1 shows a schematic of the circulation system. Two Cryomech AL330 cryocoolers were used, one in each of the two parallel helium paths. A heat exchanger is attached to each of the cryocoolers. Each helium path is equipped with a circulator to provide helium flow. The two circu-
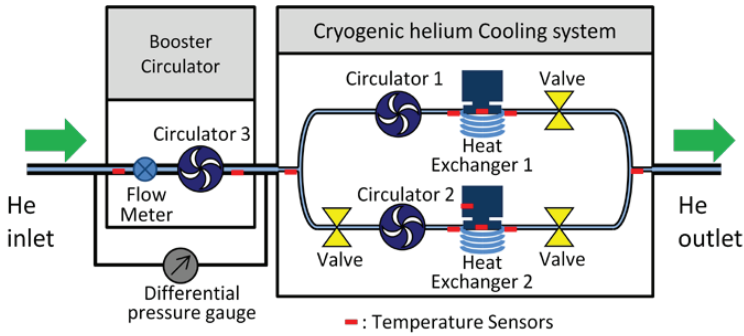
Figure 1. Schematic of the helium circulation system including two cryocooler/heat exchangers, three circulators, three valves, flow meter, differential pressure gauge and nine temperature sensors.
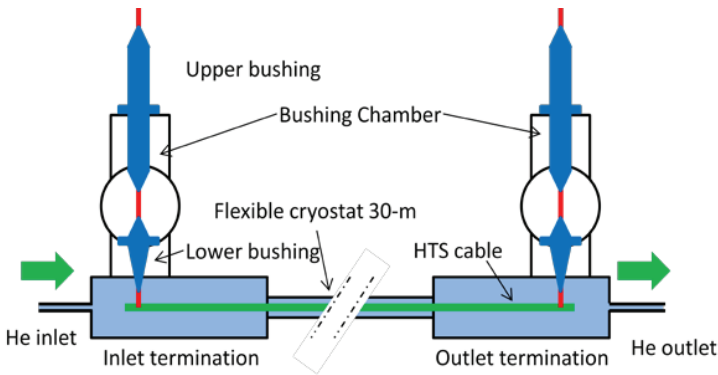

Figure 2. Schematic of 30 m long cryostat housing HTS cable and two terminations.

lators can be independently controlled to vary the speed up to 90,000 rpm. The two parallel gas streams are joined at the inlet and outlet of the circulation system forming the helium circulation available for cooling a given superconducting power application. By using the three valves, either or both of the parallel paths can be turned active during the operation. The two cryocoolers and associated heat exchangers, the two circulators, and the three valves were connected using stainless steel piping with VCR fittings. All the above components are fitted on the top flange of a large vacuum tank housing using multi layer insulation. In addition to the two circulators, a third circulator housed in a separate vacuum tank is also used. The three circulators along with the two cryocoolers and associated heat exchangers form the cryogenic circulation system used for the experiments described in this paper.

Figure 2 shows a schematic of the 30-m long cryostat housing a high temperature superconducting cable and the two terminations forming an example application that was cooled with the circulation system described above. The application was connected to the circulation system using flexible vacuum-jacketed transfer lines with bayonet connections. The cold gas from the circulation system enters inlet termination, cools the 30-m superconducting cable, and exits the outlet termination to return to the circulation system to close the circulation loop. Each termination unit is designed to serve as the interface between the superconducting power cable system and the external power system. As such, the terminations function as current leads and high voltage bushings for the superconducting cable. The particular set of terminations used in this study is designed for nominal power ratings of 3 kA and 1 kV. Heat leak into termination from ambient is reduced by a vacuum space above the gaseous helium section. The current leads/bushings are optimized to minimize heat leak from the ambient. The 30-m flexible cryostat used is made by Nexan and has inner and outer
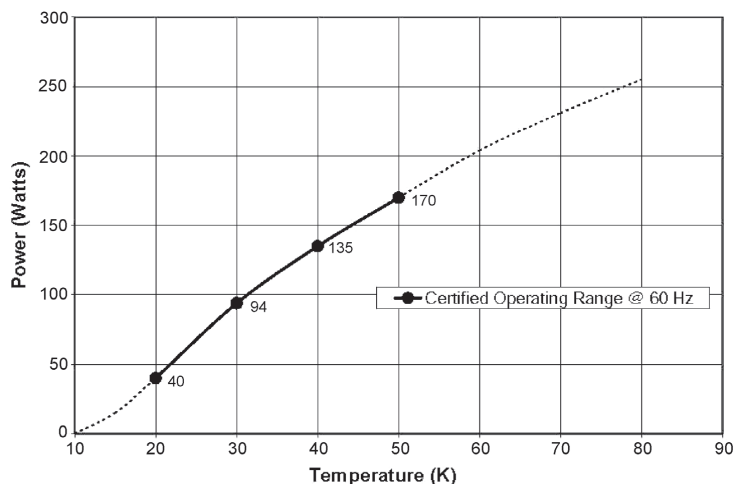
Figure 3. Cryomech AL330 capacity curve [19].

diameters of 39 mm and 66 mm, respectively. The cryostat has a nominal heat leak of 1-2 W/m. Previous experiments on the terminations have shown that the heat load on the cryogenic system from the terminations is about 40 W each.

Description of the Components of the Circulation System

Cryocoolers

Each of the two cryocoolers is model AL 330 manufactured by Cryomech [17] and has a nominal cooling power of 250 W at 77 K. The cooling capacity drops at lower temperature as shown in Fig. 3.

Heat Exchangers

The heat exchangers attached to each of the cryocoolers have proprietary design and are custom manufactured by American Superconductor Corporation to match the AL330 cryocoolers.

Circulators

The helium circulators are variable speed centrifugal pumps designed by R&D Dynamics Corporation to be used in cryogenic gas circulation applications. The design is optimized to minimize the heat leak into the helium cryogenic environment. The motor of the circulator stays at room temperature and the impeller is connected by a shaft.

Valves

The three valves used in the circulation system are Model 0840-GM manufactured by Technifab.

Cryogenic Temperature Sensors

The circulation system is fitted with nine calibrated CERNOX™ (Lakeshore model CX-1050-SD- HT) cryogenic temperature sensors to measure the temperature of the cold heads, heat exchangers, and the inlet and outlet gas streams. There are two additional temperature sensors at the inlet and outlet of the gas in the vacuum chamber housing the serial circulator.

Absolute Pressure and Pressure Drop Measurements

The absolute pressure was measured using OMEGA cryogenic pressure transducer (Model PX1005L1-500AV) with a process meter (Model DP250B). The pressure drop across the serial circulator 3 in Fig. 1 was measured using OMEGA differential pressure gauge (Model PX760).

Volumetric Flow Measurements

The volumetric flow rate of the helium gas was measured using turbine type Hoffer volume flow meter (Model HO1X1-45-BP) and housed with the serial circulator.

Mass Flow Rate Calculation

The mass flow rate of the helium gas stream, $\dot{m}$ was calculated using $\dot{m} = \rho \dot{V}$, where ρ is the density of the helium gas and $\dot{V}$ is the measured volumetric flow rate. Helium density was obtained using HEPAK at measured pressure and temperature.

Measurement of Temperature Gradients across 30-m Long Superconducting Cable System

Temperature gradients across the 30-m superconducting cable system were measured at various mass flow rates using a set of calibrated CERNOX™ sensors (Lakeshore model CX-1050-SD-HT) located at the inlet and exit of the termination tanks.

System Control and Data Acquisition System

During the experiments, absolute pressure, differential pressure, volume flow rate, and temperatures at various locations are continuously measured using high accuracy DAQ measurement system with LabVIEW (Laboratory Virtual Instrumentation Engineering Workbench) program.

EXPERIMENTAL RESULTS AND DISCUSSION

Temperature of helium gas stream of the circulation system at various locations is highly dependent on operating system pressure, circulators' speed, configuration of circulation system, and thermal load in the loop. Primary interest of this study is in understanding the effects of the system configuration viz. number of circulators in parallel or series arrangement, circulator speed, and the system operating pressure on the cooling capacity and temperature gradient across the system. Hence, experimental data was collected at various circulator speeds and operating pressures with one, two and three circulators in operation. The maximum operating pressure was limited to 250 psi to stay within the design limits of the flexible cryostat used for the superconducting cable. Wide range of volumetric circulating flow rates was achieved by varying combinations for the circulator fans 1 and 2 setting to 100%, 75%, 50%, 37% (lower limit) and 0% to 100% power and the booster circulator fan 3 being on and off. At each set of parameters, the system was run until a stable temperature distribution was obtained (usually after 2-5 hours) to ensure thermal equilibrium of all components in the system before the data for the set point was collected.

Serial Connection of Booster Circulator

Turning on the booster circulator 3 connected in series upstream of the circulation system generates additional volume flow rate at all pressure ranges. The booster circulator speed is variable, but it does not generate additional pressure drop significant enough to investigate. Instead, by increasing operating helium pressure, wide range of differential pressures across the circulator could be obtained as shown in Fig. 4. Volume flow rate increases with an increase in the pressure drop across the serial circulator up to certain value and tapers off when differential pressure is larger than about 0.07 psia. Volume flow rate increase achieved by the serial circulator is almost constant at various speed set points of circulators 1 and 2 in Fig. 1. Thus, the circulator in series is beneficial in adding additional push to the gas flow and increases the flow rate independent of the configuration of the rest of the circulation system. Hence the nomenclature "booster circulator fan" is used.

Parallel Configuration of the Two Cooling Paths in the Circulation System

Ideally, the total flow rate obtained by a parallel connection of two independent cooling and flow paths should be the sum of the flow rates of each of the paths. However, due to the flow restriction along the paths and temperature dependent cooling power of the cryocoolers (Fig. 3), the effectiveness of parallel connection of cooling paths is less than perfect. Fig. 5 shows the volume
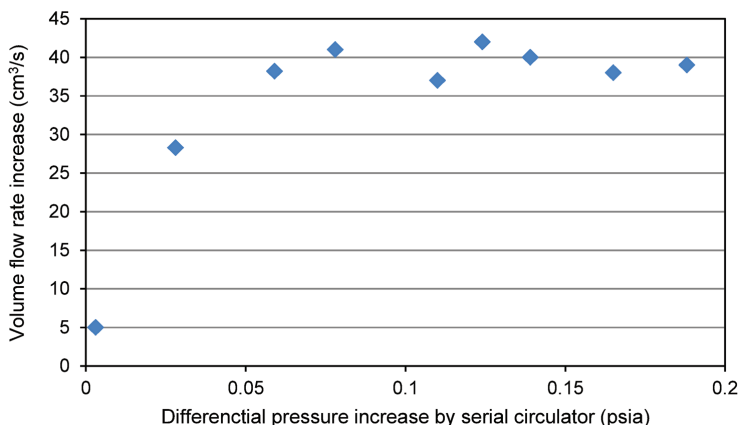
Figure 4. Volume flow rate increase due to booster circulator connected in series
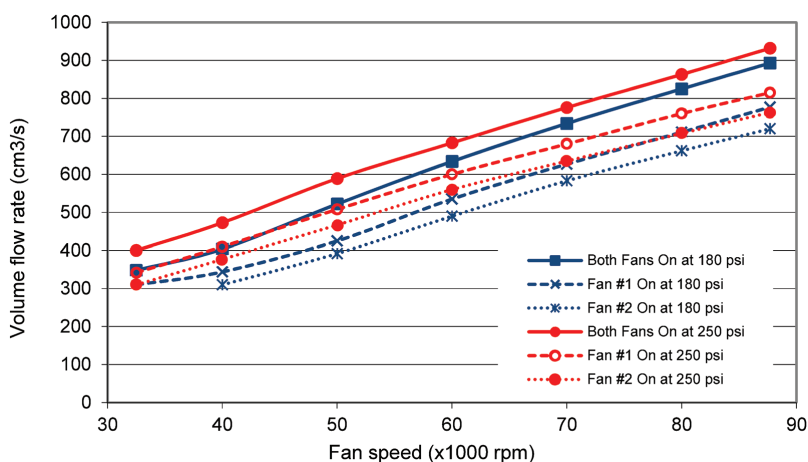

Figure 5. Volume flow rate created by parallel circulators at various fan speeds

flow rate obtained by the two parallel circulators at various set points of speeds and pressures. At higher pressure the volume flow rate is slightly larger because flow becomes more viscous around impeller in the circulators. Compared to using a single circulator, use of a second circulator in parallel configuration increases volume flow rate by 25-30%. However, available raw cooling power of the system is directly proportional to the number of paths because each parallel path has a cryocooler.

Cooling Power Capacity of the Circulation System

Total useful cooling power of the circulation system for a given operating pressure is represented by the mass flow rate and temperature drop between the inlet and outlet of the circulation system as

$$Q = \dot{m}C_p\Delta T \qquad (1)$$

where $\dot{m}$ is the calculated mass flow rate and C_p is the heat capacity at the given condition calculated by HEPAK. The temperature drop ΔT, is the measured temperature across the cooling system. The temperature drop is determined by the thermodynamic and fluid dynamic characteristics of the flow. The primary thermodynamic properties include the cooling power of each of the cryocoolers, the heat capacity of the helium gas, the heat transfer between cold head and the heat exchanger, and
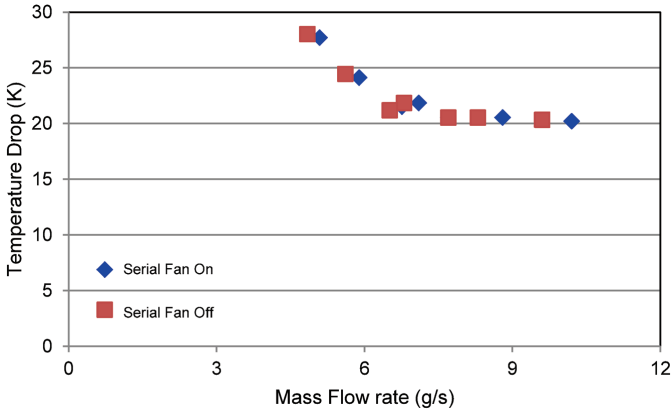
Figure 6. Temperature drop achieved by the helium gas circulation system as a function of mass flow rate.

the thermal load in the loop from the heat leak from the environment. Fluid dynamic properties are circulator flow speed, Reynolds number of the flow, plumbing structure of the circulation system, etc. Temperature of the returning helium gas to the circulation system is determined by the heat load from the superconducting power application and the available cooling capacity.

Out of many characteristic thermal and fluid dynamic properties, mass flow rate was selected for this study since it represents thermal capacity of carrying gas through the circulation system as a constant parameter regardless of location. The returning gas to the cryogenic circulation system is higher as the helium gas carries more heat throughout the circulating path and also as mass flow rate of helium is small. At the same heat leak condition, lower helium pressure, slower flow velocity, and higher exit gas from cryocooler results in higher returning gas temperature. Higher temperature of returning gas produces generally higher exit gas temperature. However, at higher operating temperature the cooling capacity of cryocoolers increases as well. Therefore, stable temperature at the heat balance between heat leak and cryocooler cooling power can be established. Fig. 6 shows the temperature drop achieved by the cryogenic circulation system as a function of the mass flow rate. The temperature of the returning helium gas ranges from 66 K to150 K, depending on heat load from the application and the gas transfer lines. As mass flow rate increases, temperature of the returning helium gas decreases and the corresponding cooling capacity of the cryocoolers decreases (Fig. 3). Hence, as the mass flow rate increases, more cooling power is carried by helium gas and returning gas temperature drops and the operating temperature of cryocoolers becomes low. Therefore, temperature drop provided by the circulation system decreases and reaches a limit for flow rate higher than 7 g/s at about 20 K. One of the reasons for the limited temperature drop at higher flow rates is the size of the heat exchangers attached to the cryocoolers. Fig. 6 shows that the additional flow speed created by the serial circulator increases mass flow rate slightly. At lower mass flow rate (less than about 7 g/s), decreased circulation could get slightly additional cooling by the cryocooling system. The returning gas has slightly higher temperature because the gas absorbs heat leakage for longer time but is cooled down to the same temperature. This means that at this mass flow rate the heat exchanger could provide more cooling as more helium gas passes through. However, at higher mass flow rate (more than about 7 g/s), decreased circulation does not seem to get higher temperature for the returning gas, and the temperature drop stays the same. This implies the heat exchanger works at maximum load balanced with the heat leak.

Using the mass flow rate and temperature drop achieved by the circulation system, effective cooling capacity (heat removal rate) of the circulation system is calculated and the data is shown in Fig. 7. Helium flow at this density regime is highly turbulent (Re>10^5) and the heat transfer in the heat exchanger is efficient. Cooling power of the cryocoolers decreases as cold head temperature decreases. For helium gas mass flow rate up to 7 g/s, the cooling capacity increases with the mass flow rate. Therefore, the operating temperature of a given superconducting power system applica-
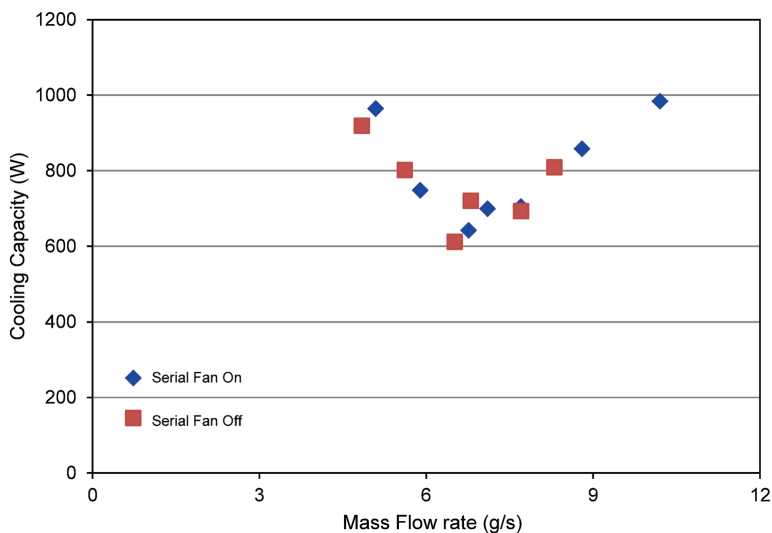
Figure 7. Calculated cooling power of the circulation system

tion can be lowered by increasing the mass flow rate. As a result the cryocoolers operate at lower temperatures and the total cooling capacity of the circulation system becomes smaller as the mass flow rate increases. However, when the mass flow rate is larger than 7 g/s, the heat exchanger size limits the heat transfer to the cold heads and overall temperature of the circulation system increases, which increases the cooling capacity of the cryocoolers and the circulation system, ignoring the dynamic losses of the circulator and the plumbing structure. Hence the design of a helium circulation system has to be optimized based on the required cooling capacity for a given superconducting power device application at the intended operating temperature. The optimization should involve sizing the heat exchangers and the circulator fans for required flow rate based on the characteristics of the cryocoolers used.

Previous study using a Stirling cryocooler estimated the heat leaks in the termination at about 50 W each and 80 W from the 30-m cryostat. In addition to the estimated heat leak from the terminations and cryostat, this experiment introduces additional heat leaks from the booster circulator fan housing and the circulation system housing. It is possible to obtain lower operating temperatures and higher effective cooling power by reducing the heat leak from the two vacuum housings. Better thermal insulation and optimized plumbing path length in the circulation system and other components will enhance the overall effectiveness of the system.

Example of a Superconducting Cable System Cooled by helium circulation

A high temperature superconducting cable system cooled by helium circulation was recently demonstrated at The Florida State University Center for advanced power Systems, The mass flow rate used in the application was in the same range as obtained by the circulation system described in this study. The operating temperature of the cable system was around 55 K. During the demonstration, DC current up to 5.5 kA was run through a 30-m long superconducting cable. Fig. 8 shows the temperature rise across the superconducting cable system application measured as a function of the mass flow rate as described in Fig. 2. The bushing chamber for this experiment was filled with liquid nitrogen for better heat blockage through current bushing into cryogenic helium flow. As can be seen in the figure, temperature gradient across the 30-m cryostat was achieved as low as 4 K. The fact that small temperature gradient can be achieved in a superconducting device demonstrates the applicability of cryogenic helium circulation systems similar to the system described in this study.
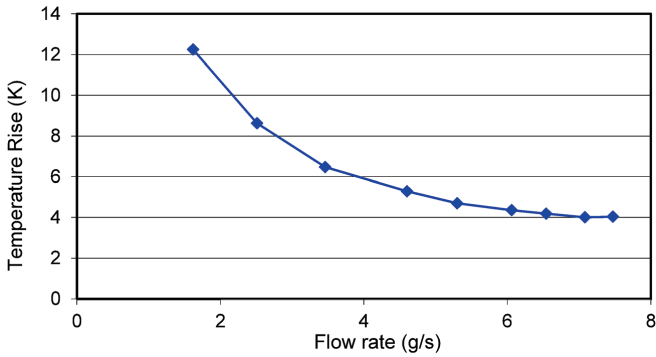
Figure 8. Temperature rise across 30 m superconducting cable system cryostat as a function of mass flow rate

CONCLUSIONS

The results presented demonstrate that superconducting power devices can be cooled using cryogenic helium gas circulation. Cryocoolers can be used as the source of cooling power for circulation systems. The design of the circulation system has to take into account the operating temperature and heat load of the application as well as both thermodynamic and fluid dynamic characteristics of the helium flow. Temperature dependent cooling capacity of the cryocoolers and heat exchanger size are also important considerations. Helium circulators and heat exchangers have to be sized to provide the required mass flow rate and if necessary multiple circulators have to be arranged in serial and parallel configurations based on the expected pressure drop created by the application, the heat exchangers, and the plumbing network.

ACKNOWLEDGMENT

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