Development of a Brassboard Active Magnetic Regenerative Refrigeration System for Low Temperature Remote Cooling

Weibo Chen[1], Nicholas Kattamis[1], Shahin Pourrahimi[2]

[1]Creare LLC. Hanover, NH 03755
[2]Superconducting Systems Inc. Billerica, MA

ABSTRACT

This paper reports on the development of a brassboard Active Magnetic Regenerative Refrigeration (AMRR) system for space applications. The AMRR is designed to continuously provide remote/distributed cooling at temperatures in the range of 2 K with a heat sink above 11 K. The warm end temperature is currently limited by the operating temperature of its superconducting magnets. The key enabling technologies for the AMRR include (1) a bi-directional circulator to circulate helium bidirectionally through the magnetic regenerators, (2) two highly effective active magnetic regenerators with a structured matrix to enable the AMRR to achieve high thermal efficiency, and (3) two advanced low-current, lightweight superconducting magnets that produce a gradient magnetic field with an optimum temporal and spatial distribution to enable the AMRR system to achieve high thermal efficiency. This paper first discusses the overall system design considerations. It then discusses the design and fabrication challenges for the key components. Next, it describes a brassboard system to assess the performance of a brassboard AMRR. Finally, the paper discusses future research directions to further advance the AMRR technology.

INTRODUCTION

A critical need for future astrophysical observation is the capability to provide multi-year cooling for low-noise detector systems operating at temperatures below 4 K. Low-temperature cooling reduces the thermal emission of the detectors themselves and enhances their sensitivity and resolution. The duration of these missions is typically more than five years. Using consumable stored cryogens for these missions will lead to a large system mass and is undesirable, especially for large space telescopes. AMRR systems are uniquely suitable for these applications because of their potential for very low temperature cooling capability, high thermodynamic efficiencies, and high reliability.

AMRR SYSTEM OVERVIEW

An AMRR system is a very efficient thermodynamic cycle that utilizes the magnetocaloric effect to produce refrigeration at temperatures down to about 2 K [1] [2] [3]. In an AMRR system, a circulating fluid interacts with a magnetocaloric material in the regenerator to facilitate heat transfer

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within the material along the axial direction. This creates a cascade effect that allows the system to reject heat at a high temperature. The circulating fluid also allows the AMRR to provide remote cooling for detectors that are located far away from the cooler.

Key components in an AMRR system include two identical Active Magnetic Regenerators (AMR), their surrounding superconducting (SC) magnets, and a bi-directional circulator (Fig. 1). Each regenerator has a heat exchanger (HX) at its warm end to reject its magnetization heat to a heat sink, and the two regenerators share a cold end load heat exchanger to absorb heat from a cooling target. The magnetic fields in the regenerators operate 180° out of phase with respect to each other—magnetizing one regenerator while demagnetizing the other. The circulator is a centrifugal bi-directional pump using self-acting gas bearings. It controls the flow direction in sync with the magnetic fields to facilitate heat transfer. During operation, helium enters the hot end of the column being demagnetized, is cooled by the magnetic refrigerant, and passes into the cold end heat exchanger to absorb heat. The helium then enters the cold end of the column being magnetized, absorbs heat from the refrigerant, and enters the hot end heat exchanger to reject the magnetization heat.

AMRR SYSTEM DESIGN CONSIDERATIONS

Key System Design Parameters

The key system design parameters include the magnetic refrigerant material, cycle working fluid and its pressure, the maximum and minimum magnetic field strengths, and the cycle period. Once these parameters are determined, the working fluid shuttle mass, the magnetic refrigerant mass in each regenerator, and the magnetic field spatial and temporal profiles can be optimized by numerical analyses for a given cooling requirement [4].

The most common magnetic refrigerant, gadolinium gallium garnet (GGG), is used in our baseline design because its magnetocaloric effects and other thermodynamic properties are well-characterized and the material is readily available. The circulating fluid is subcritical ^{3}He with a pressure slightly below its saturation pressure corresponding to the AMRR cold end temperature to prevent condensation at the cold end of the regenerator. Supercritical ^{3}He is not considered because of its very high specific heat near its critical temperature, which severely limits regenerator thermal efficiency. Our thermodynamic analyses show that the maximum field strength in a GGG regenerator needs to be about 2 T for the cold end section at about 2 K and about 5 T for the warm end section above 12 K [4].

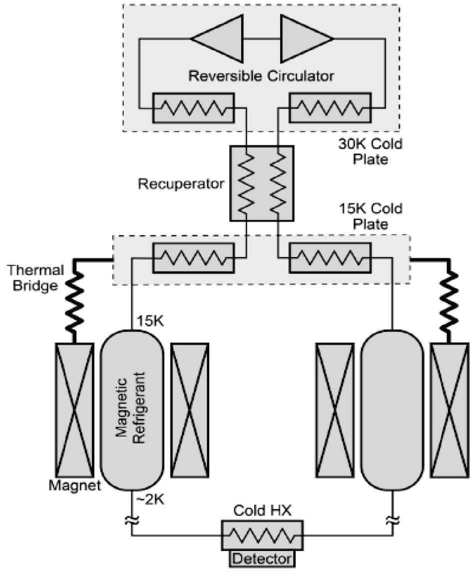

Figure 1. System schematic of an AMRR with a bi-directional circulator.

Factors Limiting Cycle Period

In general, reducing the cycle period will proportionally increase the system cooling capacity. However, in actual applications, the minimal cycle period is limited by three factors: The first is the response time of the bi-directional circulator during the flow switching process. Because the moment of inertia of the miniature impellers in Creare's circulator is very small, the bi-directional circulator can switch flow direction very quickly, within about 1 s. Thus, the circulator is not a limiting factor for the cycle period. The second is the AC loss in the superconducting magnets. As the cycle frequency increases, the parasitic heating power due to AC losses in the SC magnets more than proportionally increases, increasing the risk of quench in the superconducting coil. Our preliminary testing shows that as the cycle period is reduced below 60 seconds, the superconducting magnets could become a limiting factor for the cycle period based on current thin-wire superconducting magnet technology. The third is the minimum ratio of ^{3}He shuttle volume during a cycle to the void volume between the regenerator warm end precooler and the cold end load heat exchanger. This ratio needs to be appreciably larger than 1 to ensure that magnetization heat in the regenerator can be carried to the heat sink by the circulating flow and the regenerator cooling power can be effectively transferred to the load heat exchanger, as discussed below.

Void Volume Effects on AMMR Performance

The void volumes between the regenerator core and its adjacent heat exchangers have significant impact on the AMRR performance. These void volumes prevent all the gas exiting the regenerator matrix from reaching the respective heat exchangers, reducing the overall thermal performance of the AMRR. On the warm end, the void volume between the regenerator and the precooler reduces the amount of gas reaching the heat sink during the cold-to-warm blow process and increases the fluid temperature entering the regenerator at the beginning of the warm-to-cold blow process. After the cold-to-warm blow process, an amount of working fluid is trapped in the void volume between the regenerator and precooler. The temperature of this fluid will be greater than the temperature of the fluid leaving the precooler. During the cold-to-warm blow process, the average fluid temperatures exiting the warm end of the regenerator must be higher than the heat sink temperature so that the working fluid can reject magnetization heat to the heat sink. At the beginning of the warm-to-cold blow process, the trapped warm gas reenters the regenerator. The warm gas raises the warm end temperature until all the trapped gas has entered the regenerator, as shown in Fig. 2.

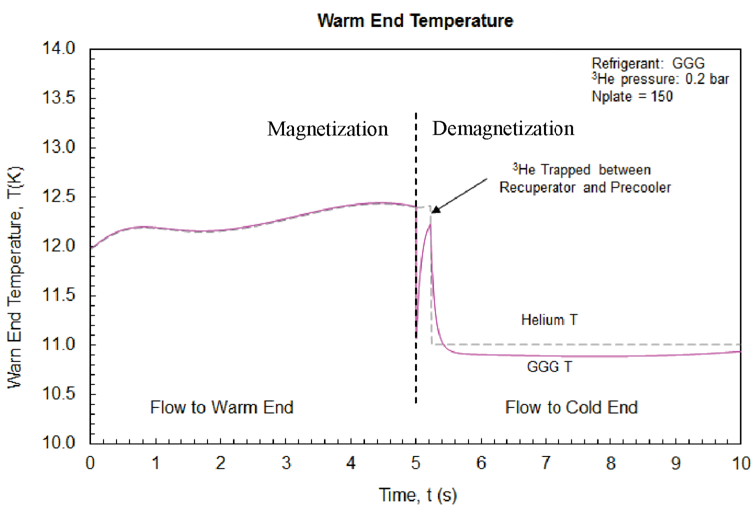

Figure 2. Predicted temperature of ^{3}He flow at the warm end of regenerator. Results are shown for the design condition with a warm end heat rejection temperature of 11 K. Dotted line is helium gas temperature at the warm end.

On the cold end of the regenerator, the void volume between the regenerator and the load HX reduces the amount of gas exiting the regenerator cold end from reaching the load heat exchanger during the warm-to-cold blow process, and thus reduces the cooling available for the load heat exchanger. Note that the trapped cold fluid will enhance cooling for the regenerator during the cold-to-warm blow process, partially offsetting the associated performance penalty. The void volume at the cold end has a stronger impact than that at the warm end on the system performance because the shuttle gas volume at the cold end is much smaller than at the warm end.

Void Volume Effect on AMRR Cycle Time and Design

The performance penalty associated with the void volumes is approximately proportional to the cycle frequency. As the cycle frequency increases, the shuttle mass of the working fluid will proportionally decrease, and the ratio of the void volume to the local shuttle fluid volume and the associated performance penalty will proportionally increase. This effect limits the maximum cycle frequency for many practical applications, especially for applications where the cooling target is located far away from the regenerators and the void volumes in the transfer lines between the regenerators and the load HX are relatively large.

The performance penalty associated with the void volumes can be mitigated by delaying the flow switching relative to the magnetic field switching. This approach involves letting the working fluid continue to exit the warm end of the regenerator after the isothermal magnetization process ends, allowing all the gas exiting the regenerator during the isothermal magnetization process to reach the precooler, enhancing the system heat rejection. Similarly, this approach lets the working fluid continue to exit the regenerator cold end after the isothermal demagnetization process ends, allowing all the gas exiting the regenerator cold end to reach the load heat exchanger, enhancing the system cooling capacity. The effectiveness of this mitigation approach will be evaluated in our brassboard AMRR system.

ENABLING COMPONENTS FOR A SPACE AMRR

The key components for an AMRR include (1) a bi-directional, vibration-free cryogenic circulator; (2) active magnetic regenerators; and (3) high-temperature, high-field-strength low current superconducting magnets. Their design requirements and development status are discussed below.

Bi-directional Cryogenic Circulator

The circulator must be able to operate at cryogenic temperatures to reduce pumping power and to reduce the recuperator size in the AMRR. It must be able to reliably and quickly reverse the flow direction without mechanical wear and with virtually no transmitted vibration. Creare's AMRR bi-directional circulator consists of two modules, each with a miniature centrifugal impeller. The circulator regulates the flow direction by varying impeller speeds relative to each other. Since the impellers are very small and their moment of inertia is very low, the circulator can switch flow direction very quickly. The cryogenic circulator design is based on Creare's non-contacting self-acting gas bearings and clearance seals for reliable and virtually vibration-free operation. For the AMRR to reach the target cooling temperature of about 2 K, the system pressure must be below 0.2 bar to prevent condensing at the cold end [5]. Operating a circulator using self-acting gas bearings at such a low pressure is challenging. We have built one of the modules for the circulator and demonstrated its ability to achieve the target pressure rise with stable operation at the design speed of 3,000 Hz in cryogenic temperatures with a system pressure of only 0.2 bar.

Active Magnetic Regenerator

The active magnetic regenerator is a regenerative heat exchanger with its matrix material made of a solid-state magnetic refrigerant that will generate heat or refrigeration during the magnetization or demagnetization process, respectively. Active magnetic regenerators serve two critical functions in an AMRR system. First, the regeneration process enables each segment of magnetic refrigerant to thermally interact with its adjacent segments via the circulating fluid, resulting in a cascaded refrigeration cycle which allows the system to operate with a heat sink temperature (about 15 K) much higher than its cooling temperature (about 2 K). This effectively extends the heat rejection temperatures of an AMRR to the range where current mechanical cryocoolers can achieve high efficiency, and therefore improves the overall efficiency of the cooling system. Second, it also enables the circulating fluid to transfer cooling power from the magnetic refrigerant to a remotely located payload(s).

The critical performance requirements for an AMR are similar to those for regenerators in Stirling and Pulse tube coolers, including high thermal effectiveness, low flow resistance, low axial conduction and low void volume. In addition, the volume of non-magnetic refrigerant material (i.e., solid spacer material) in an AMR must be minimized to reduce the size of the regenerators and thus the size and mass of the surrounding superconducting magnets. In addition, the regenerator core must be able to withstand dynamic loads induced by launch vibrations and the cyclical magnetic forces on the core. The magnetic force on the core can be appreciable because the magnetic field strength is high and the field strength has a strong axial gradient.

Creare developed a regenerator consisting of a stack of thin GGG disks separated by thin layers of thermal insulators to reduce axial conduction. A simple packed bed magnetic regenerator would have an unacceptably high axial thermal conduction. This is because GGG has a relatively high thermal conductivity up to 600 W/m-K in the operating temperature range of 2 to 15 K. Fabricating the high-aspect ratio microchannels in GGG is however challenging since it (1) cannot be chemically etched using the standard methods developed by the semiconductor industry and (2) is very brittle and prone to cracking. These fabrication challenges limit the practical channel configuration and the minimal channel feature size. We successfully used a unique microfabrication process to machine micro through-holes at a diameter of 254 microns in the GGG disks to form small flow paths for circulating helium, as shown in Fig. 3. The through holes are uniform and have very sharp

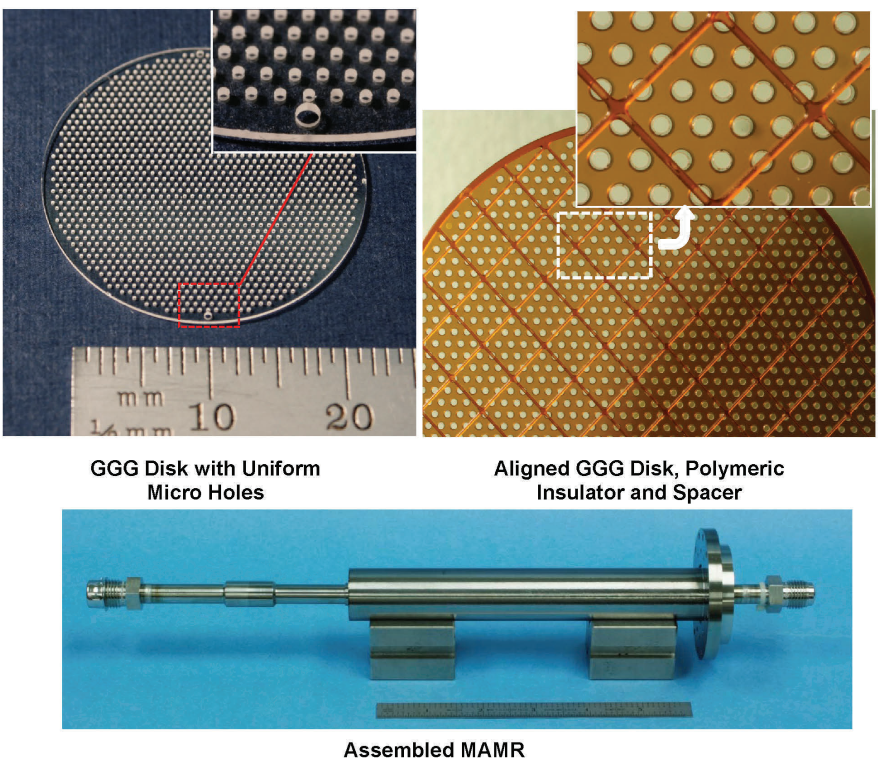

Figure 3. Micro through holes with a diameter of 254 microns in GGG wafer

entrances and the exits. The fabrication process effectively prevents mirocracking in the thin GGG wafers and tapers/burrs in the machined holes.

The holes in a given GGG plate was offset from its adjacent plates. This offset-hole configuration had significant performance benefits over a stack of aligned holes, which would form a couple of thousand parallel “tubes” extending from the warm end to the cold end in the core assembly. Although the fabrication of plates and insulation layers with aligned holes is much simpler, the performance of the regenerator would be very vulnerable to small plate misalignment. Misalignment would not only significantly increase flow pressure drop, but also cause flow maldistribution, which could lead to significant thermal performance degradation. In addition to reducing axial conduction heat leak, the spacers between the GGG plates have features to promote uniform flow distribution. Our CFD simulation and separate effects test data show the regenerator configuration achieves higher heat transfer and a much lower axial conduction heat leak for a given pressure drop than a conventional stacked screen or packedbed regenerator. Our dynamic structural test data confirmed that the GGG plates can withstand dynamic loads induced by launch vibrations and the expected cyclical magnetic forces during normal operation.

Superconducting Magnet System

The superconducting magnet in an AMRR system must generate a magnetic field with a proper spatial and temporal profile to minimize the regenerator local temperature swing during the isothermal magnetization and demagnetization processes. Its maximum field strength must be relatively high, about 5 T at the warm end of the regenerator to achieve a strong magnetocaloric effect at temperatures above 12 K. The superconducting wire must also be able to achieve a relatively high current density of about 200 to 300 A/mm^2 while operating at such a high field and at the AMRR warm end temperature to minimize the magnet size and mass. Furthermore, the magnet must use thin wires to allow low-current operation to reduce lead wire losses and simplify magnetic current supply controller design. For the AMRR application, the cycle frequency is relatively high, therefore the superconducting magnet must have low enough AC losses (heating of coils due to pulsing alternating magnetic field) to enhance system efficiency, and more importantly, to enable relatively a fast charging and discharging process without causing quenching. To reduce AC losses, superconducting filaments in the wires must be as narrow as possible. Superconducting System Inc. is developing the AMRR magnet. SSI uses several nested coils with different winding charateristics to generate the required spatial profile. Small diameter Nb_3Sn wires with filaments of 2-3 micrometers in diameter are used for the coils. The wire sizes and architecture were optimized based on the local field and stored energy of individual coils. SSI first fabricated a 2.5 T magnet with a gradient magnet field and qualified its performance. The 5 T superconducting magnet is in the final stage of the fabrication process

The energy required to charge an AMRR superconducting magnet is significant, about 500 J/cycle. If the discharged energy is not recovered, the power to energize the magnet would be about 100 W for a pair of superconducting magnets operating at a frequency of 0.1 Hz, which is unacceptably high. Therefore a power supply that captures the discharged energy from the demagnetization process, stores it in a capacitor, and supplies it back to the magnet during the magnetization process is needed. Furthermore, the power supply must be able to control the supply current temporal profile to generate a field with optimal temporal profile. Creare has designed and assembled a current controller and verified its performance with an inductor simulating the superconducting coil.

A PROOF-OF-CONCEPT BRASSBOARD AMRR

Creare is assembling a simplified brassboard AMRR to assess the performance of a low temperature AMRR. Due to resource constraints, the brassboard system only consists of one regenerator, one set of superconducting magnet, and one cryogenic circulator module. As a complete AMRR system requires two of each of these components, we incorporated additional hardware and test procedures to create a brassboard demonstration unit. In place of the second magnet and regenerator in a complete AMRR, a helium bath at reduced pressure is used to provide cooling slightly below 2.3 K for the returning gas flow entering the cold end of the regenerator (Fig. 4). Also in place of the

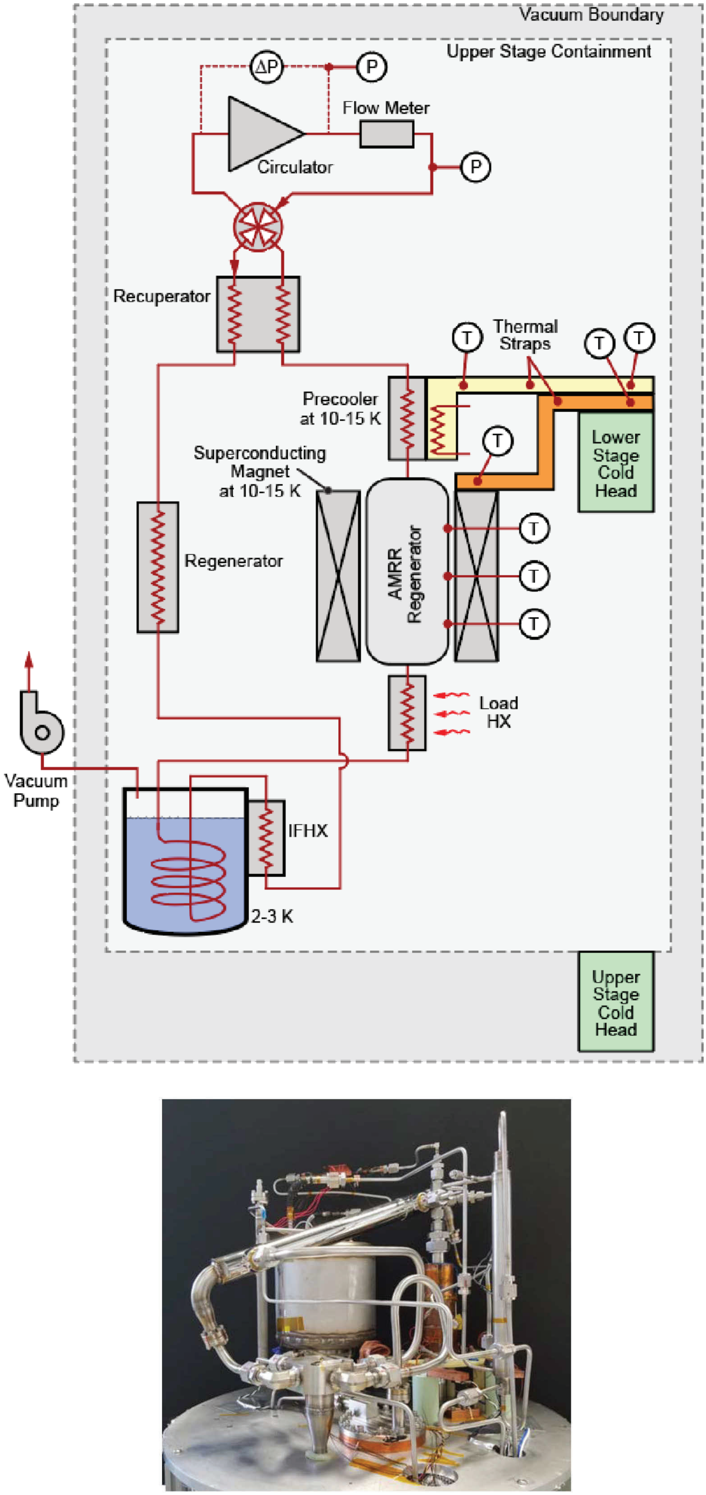

Figure 4. Simplified Brassboard AMRR for Thermal Performance Testing, top-schematic, bottom-test setup

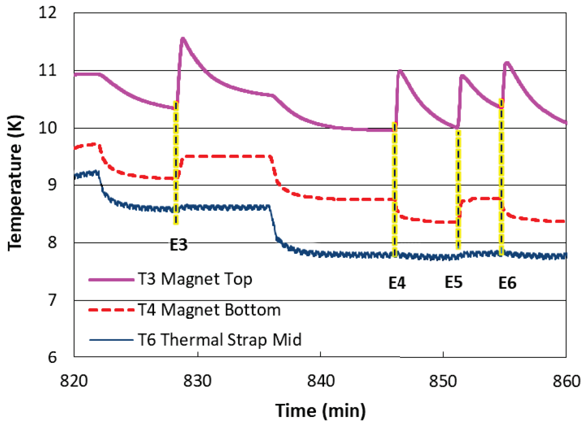

Figure 5. Temperature profiles of 2.5 T superconducting magnet and thermal bridge during charging and discharging processes

bi-directional circulator, a flowswitching valve is incorporated with a cryogenic circulator module to reverse the flow direction. The cryogenic circulator has design features to allow it to be evolved to a bi-directional circulator when coupled to the second half of the circulator.

We are in the final stages of the simplified AMRR brassboard system assembly. Because the brassboard system involves many components, before incorporating the high value cryogenic circulator and the actual AMR into the brassboard system, we conducted separate effects testing to verify that the design and operation of the auxiliary components meet our performance targets. We also used the test setup to verify several key design parameters. First, we verified that the non-prototypical loop flow resistance is low enough for the circulator to force the target flow rate through the system. Second, we verified that the magnetic force on the regenerator core is within the expected range to prevent potential damage to the micromachined GGG wafers inside the actual regenerator. For this measurement, we used a packed regenerator with a prescribed amount of small GGG beads. One end of the regenerator is connected to a load cell to measure the force exerted on the regenerator. We also used a 2.5 T superconducting magnet in place of the final magnet while the final 5 T superconducting magnet is being fabricated at SSI. Third, we obtained preliminary $NbSn_3$ superconducting magnet AC losses data and assessed the allowable fastest magnet charge and discharge time without causing the magnet to quench.

Our shakedown testing shows that the current circulator pressure rise can easily overcome the loop pressure drop at the design condition. Our testing also shows that the magnetic force on the regenerator core is within our expected range and thus we expect that the GGG wafers will be able to withstand this force and the preload force without any damage. As for the superconducting magnet, the test results shows that the charge time and discharge time for the 2.5 T magnet needs to be relatively long (~ 30 s) to prevent magnet quenching. Magnet quenching occurred for all smaller charge and discharge times. During the charge and discharge processes, the magnet temperature increased appreciably, as shown in the events at t = 828 min (E3) and 850 min (E5) in Fig. 5. This suggests that the AC losses during the magnet charge and discharge processes were appreciable. The high AC losses limits minimal charge and discharge time to prevent quenching. The resulting long charge cycle might limit the AMRR cycle frequency. These results provide background data for the design of wires for the 5T magnet, which is expected to have lower AC losses.

CONCLUSIONS AND FUTURE WORK

A brassboard system is being developed to assess the performance of an AMRR system designed for space applications. The brassboard system will assess the performance of individual components for the AMRR system and allow us to optimize the system operating parameters. The brassboard system will also allow us to assess the effectiveness of using a time delay between the magnetic switching and the flow switching to mitigate the effect of the void volumes in the AMRR.

Low temperature superconducting magnet technology is the performance limiting factor in the current AMRR. Future research in this area will focus on increasing the maximum operating temperature of the low-current superconducting wires to increase the AMRR heat rejection temperature, and on reducing its AC losses to enhance the AMRR efficiency and to allow faster charge and discharge time to reduce the AMRR size and mass.

ACKNOWLEDGEMENTS

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