A 2 K Active Magnetic Regenerative Refrigeration System for Remote Cooling

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ABSTRACT

This paper reports on the development of an Active Magnetic Regenerative Refrigeration (AMRR) system for space applications. The AMRR can continuously provide remote/distributed cooling at about 2 K and reject heat at temperatures higher than 15 K. The AMRR employs a reversible circulator to circulate helium bi-directionally through magnetic regenerators. The circulating flow facilitates the heat transfer in the magnetic regenerators. The circulator uses self-acting gas bearings for reliable and vibration-free operation. The AMRR also uses structured-bed regenerators with microchannels for high thermal performance. Demonstrations to date have shown the ability of the circulator to operate at high speeds and low sub-atmospheric pressures. Hardware fabrication for the circulator and its demonstration are near completion, while development of the fabrication method for the regenerator is in progress. The results of this research show that the AMRR system is very attractive for space applications. The AMRR will be very reliable and vibration free. The predicted COP of the AMRR system is about 35% of a Carnot cycle with cryogenic heat sinks. The system can operate at the very short cycle period of 10 seconds to achieve a large cooling capacity. The AMRR's ability to provide remote/distributed cooling not only allows flexible integration with payload(s) and spacecraft, but also reduces the mass of the required magnetic shields.

INTRODUCTION

NASA's strategic road map for space exploration includes successive future missions to probe the origin of stars and galaxies in the early universe. These missions will require the use of infrared, X-ray, and gamma ray science satellites and future space telescopes. A critical need for these missions is the capability to provide multi-year cooling for low-noise detector systems in the temperature range from 4 K to subkelvin. The low temperatures are required to reduce the thermal emission of the detectors themselves and to achieve high sensitivity and resolution. The duration of these missions is typically more than five years, making stored cryogens a heavy and undesirable option, especially for large space telescopes. Magnetic coolers are uniquely suitable for these applications because of their very low temperature cooling capability, high thermodynamic efficiency, and high reliability (Shirron et al.[1,2], DiPirro and Shirron[3]).

A magnetic cooler utilizes the magneto-caloric properties of materials to produce refrigeration. When a magnetic field is applied adiabatically to a magnetic refrigerant, the magnetic moments of

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the refrigerant molecules will align with the applied field. As a result, the magnetic entropy decreases and the refrigerant heats up because the total entropy must be conserved. When the field is removed, the magnetic refrigerant becomes randomly oriented. Its magnetic entropy increases and the refrigerant cools down. The magnetization and demagnetization processes of the magnetic refrigerant are analogous to the compression and expansion processes of a gas. The thermodynamic cycle of a magnetic cooler employing the Carnot cycle, which consists of two isothermal and two adiabatic magnetization/demagnetization processes, is shown in Figure 1 as cycle 1-2-3-4.

The heat transport mechanism (i.e., heat switches and thermal buses) in current multistage magnetic coolers is not very effective or lightweight. In addition, current magnetic coolers cannot cool remote targets, necessitating heavy magnetic shielding to prevent the magnetic fields of the coolers from interfering with the nearby detectors. These shortcomings not only increase the system mass, but also impose significant constraints in the system design. Thus, there is a strong need for a magnetic cooler with a fluid circulation loop that will improve heat transfer and provide remote cooling.

To overcome these existing limitations, Creare with the support of NASA began the development of an Active Magnetic Regenerative Refrigeration (AMRR) system that can provide continuous remote cooling down to about 2 K and reject heat at temperatures higher than 15 K. The AMRR system is shown in Figure 2. The AMRR mainly consists of two identical magnetic regenerators, surrounded by their superconducting magnets and a reversible circulator. Each regenerator has a heat exchanger at its warm end to reject the magnetization heat to a heat sink; and the two regenerators share a cold end heat exchanger to absorb heat from a cooling target. The magnetic fields in the regenerators operate 180 degrees out of phase with respect to each other.

The AMRR employs a reversible circulator to circulate helium bi-directionally through the magnetic regenerators. The circulator controls the flow direction, which cycles in concert with the magnetic fields to facilitate heat transfer in the regenerators. Helium enters the hot end of the demagnetized column, is cooled by the refrigerant, and passes into the cold end heat exchanger to absorb heat; the helium then enters the cold end of the magnetized column, absorbing heat from the refrigerant, and enters the hot end heat exchanger to reject the magnetization heat. The efficient heat transfer in the AMRR allows the system to operate at a relatively short cycle period to achieve a large cooling power. The effective heat transfer also enables an active regeneration process in the regenerators. Consequently, the temperature span of each refrigerant segment can be very small,

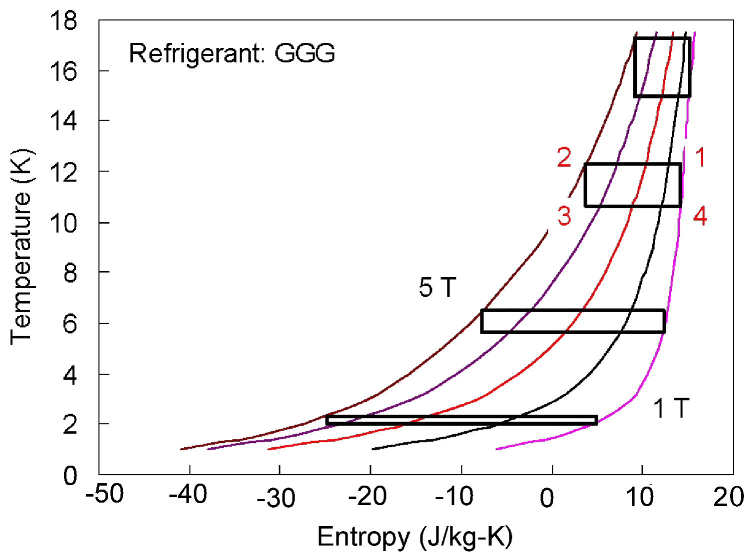

Figure 1. T-S diagram for magnetic cooler.

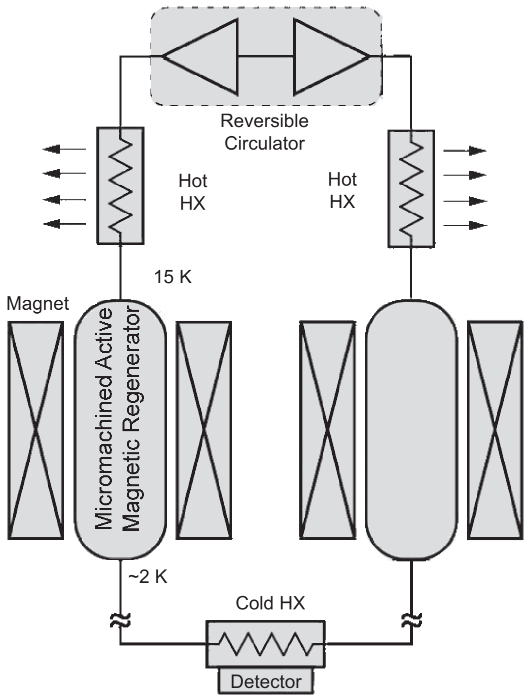

Figure 2. System schematic of an AMRR with a reversible circulator.

but the overall regenerator temperature span can be more than 10 K. The circulator enables remote distributed cooling, allowing a detector(s) to be located far away from the cooler and thereby reducing the size and mass of magnetic shields.

The key mechanical components in the AMRR are the reversible circulator and the magnetic regenerators. The circulator design is based on Creare's non-contacting, self-acting gas bearings and clearance seals; these result in long life and vibration-free operation. There are no valves or mechanical wear in this circulator. Its reliability has been demonstrated to be very high and suitable for long-duration space missions. The magnetic regenerator employs a structured bed configuration. The core consists of a stack of thin Gadolinium Gallium Garnet (GGG) disks alternating with thin polymer insulating films. The structured bed reduces flow resistance in the regenerator and therefore the pumping work by the cryogenic circulator. The GGG plates also have a unique channel configuration that ensures temperature uniformity across the plates. The insulating layers are used to reduce axial conduction heat leak, because GGG has a very high thermal conductivity in the regenerator's operating temperature range.

AMRR SYSTEM DESIGN OPTIMIZATION

At the early stage of the cycle analysis, proper values or ranges of several key system design parameters were determined. The first parameter is the pressure of the circulating ^{3}He. It was found that the very high specific heat of supercritical ^{3}He near its critical temperature poses a severe limitation to the thermal efficiency of the regenerators. Furthermore, it was found that the ideal magnetic field required for the AMRR has a relatively sharp spatial peak near locations where the temperature is near the ^{3}He critical temperature. Consequently, a regenerator with supercritical ^{3}He cannot achieve a high thermal efficiency when it is driven by practical superconducting magnets. For this reason, low-pressure subcritical ^{3}He was selected as the thermal transport fluid. The pressure of the subcritical ^{3}He was selected to be just below the saturation pressure corresponding to the AMRR cold end temperature.

The second system parameter considered is the cycle period. Reducing the cycle period will proportionally increase the system cooling capacity. The minimal cycle period is limited by three factors: (1) the efficient operation of the reversible circulator associated with the flow switching process; (2) the minimum ratio of ^{3}He shuttle volume by the circulator to the regenerator void volume—this ratio needs to be larger than one to ensure that magnetization heat in the regenerator can be carried to the heat sink by the circulating flow; and (3) performance limitation of the electromagnetic system. These considerations led to the selection of a cycle period of 10 seconds.

The third system parameter is the magnitude of the magnetic field swing. It was found that, based on thermodynamic properties of GGG, the magnetic work input to the regenerator is very small as the magnetic field approaches zero. Therefore, it is not necessary to reduce the filed below 1 Tesla. A magnetic field higher than 5 Tesla will be difficult to achieve with superconducting magnet technology in the near future, and a higher field will only benefit the warm end of the regenerator. These considerations led to the selection of a magnetic field range of 1 to 5 Tesla to drive a GGG regenerator.

The AMRR system design activities include: (1) optimization of magnetic field for the regenerator by practical superconducting magnets; (2) preliminary component design and analysis of the magnetic regenerators, the reversible circulator, the superconducting magnets, and auxiliary heat exchangers; and (3) preliminary integrated system layout design and analysis to estimate system size and mass.

Following the optimization activities, a preliminary system design for space applications was developed, as shown in Figure 3. Its performance and mass estimates are summarized in Table 1. The system is designed to provide 64 mW of cooling at 2.3 K. In this design, the circulator operates at about 30 K, and its predicted power input is about 890 mW. The recuperator in the system enables the circulator to operate at a temperature above the regenerator warm end temperature. The predicted heat dissipation from the regenerators is about 627 mW. The overall system COP is about 35% of Carnot COP. Assuming the COP of the upper stage mechanical cryocoolers is 10% of Carnot COP, the COP of the overall cryocooler system can still be higher than 3% of Carnot COP with a heat sink at 300 K.

The estimated system mass is about 3.1 kg. The circulator constitutes about 40% of the system mass, and the regenerators make up only about 13% of the system mass. Almost all the system pressure drop occurs in the regenerators.

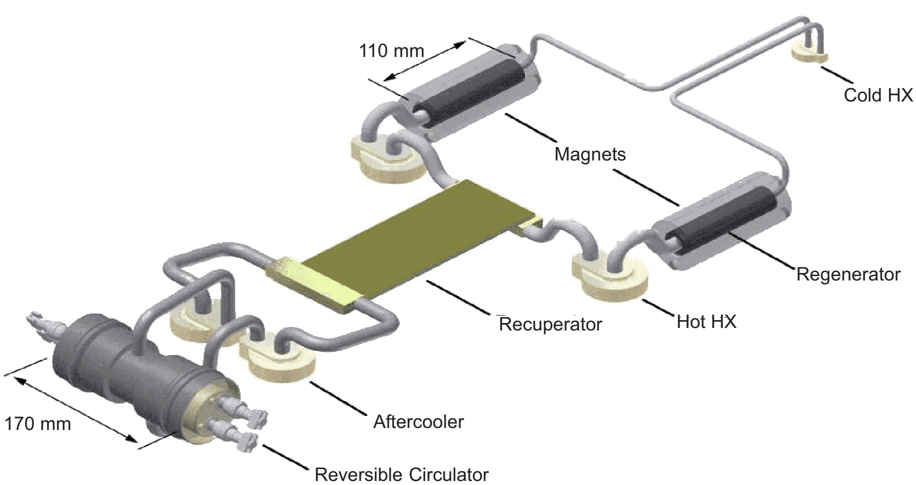

Figure 3. An integrated AMRR system design. It weighs only 3.1 kg for a cooling power of 64 mW at 2.3 K.

Table 1. Performance and mass estimates for a space AMRR system using GGG refrigerant.

Cooling Temperature	2.3 K
Cycle Period	10 sec
Magnetic Refrigerant	GGG
Maximum Magnetic Field	5 T
Cooling Capacity	64 mW
Heat Rejection 1, at 15 K	627 mW
Heat Rejection 2, at 30 K	890 mW
System COP (% Carnot COP)[1]	35%
System Mass	3.1 kg
Mass of Each Regenerator	0.20 kg
Circulator Mass	1.3 kg

[1] Does not include loss in the SC magnets.

AMRR CRITICAL COMPONENT DEVELOPMENT

Hardware fabrication and testing efforts are in process to demonstrate the operation of key mechanical components in the AMRR system. The status of these efforts is briefly discussed below.

Circulator Fabrication and Testing. A test facility with prototypical features has been set up (Figure 4) to demonstrate that the rotating assemblies in the circulator can operate stably at the design speed of 3000 Hz, even when the system pressure is only 0.2 bar. As discussed before, enabling the circulator using self-acting gas bearings to operate at this low pressure is the key for the magnetic cooler to reach a cooling temperature of about 2 K. This is the biggest technical challenge for the circulator.

Ultra-high precision surface machining and a wear resistant surface coating were used to achieve very thin converging gas films, and thereby increase the bearing support force. Figure 5 presents the runout of the test rotating assembly at the forward journal bearing, measured during low-pressure testing. The plot shows that the runout amplitude at a rotational speed of 3,000 rev/s and an

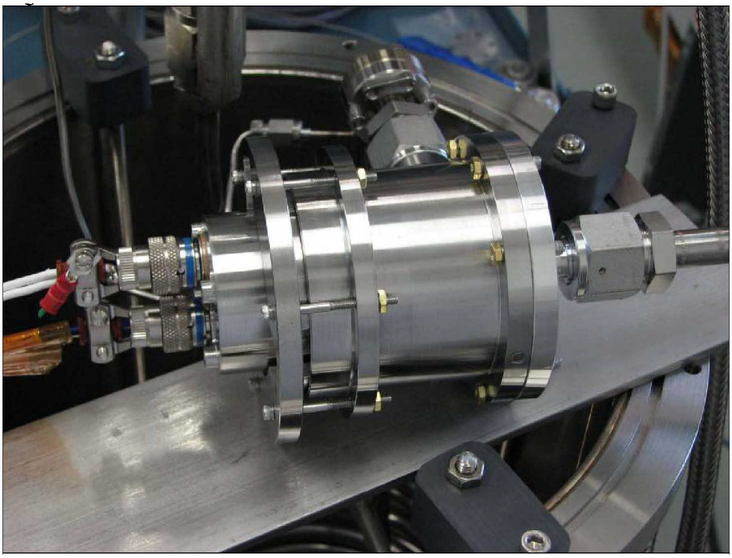

Figure 4. Circulator test facility during low pressure bearing stability testing.

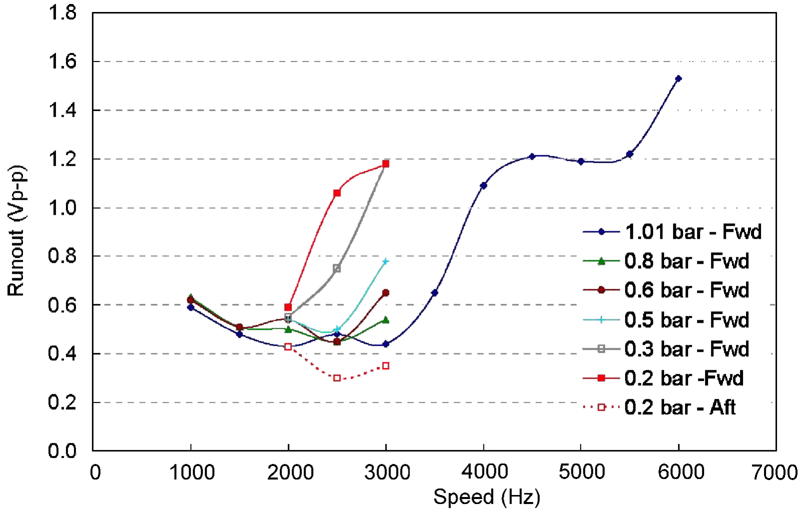

Figure 5. Shaft runout amplitudes during reduced pressure testing.

operating pressure of 0.2 bar is approximately equal to the amplitude at 5,000 rev/s at ambient pressure. Furthermore, the rotor can be operated stably with runout amplitudes considerably larger than those seen at the 0.2 bar operating condition, as shown in the ambient pressure runout curve. These results are consistent with Creare's empirical bearing design model and indicative of stable operation of the full reversible circulator at design conditions. The circulator aerodynamic performance testing is currently under way.

Regenerator Fabrication Development. Creare is currently working on the detailed thermal and fluid design of the regenerators, as well as their fabrication process. In this design, GGG is used as the refrigerant material. This regenerator design calls for microchannels with a width less than 100 microns to enhance heat transfer. Each GGG plate also must have an integrated polymer layer with an identical flow channel configuration, to reduce axial conduction and the void volume in the regenerators. The flow channels in the insulating layers must precisely align with those in the GGG plates. These design requirements pose a significant fabrication challenge, because GGG cannot be chemically etched using the standard methods developed by the semiconductor industry. GGG is also very brittle, further increasing the challenge in micromachining processes. Fabrication trials to use a combination of different micromachining approaches to produce the microchannels in the composite plates are currently under way.

CONCLUSIONS

This study describes an AMRR system that can provide cooling at about 2 K and reject the heat at 15 K. The AMRR can provide remote distributed cooling to simplify system integration. It has a unique reversible circulator that uses non-contacting gas bearings to achieve vibration-free and highly reliable operation. The AMRR also employs a micromachined regenerator to enhance its thermal and fluid performance. Research to date has identified the optimum spatial and temporal magnetic field distributions for the magnetic regenerators using practical SC magnets. A numerical analysis model was developed to estimate the magnetic regenerator performance. Preliminary design analysis shows that the AMRR can achieve a COP of about 35% of a Carnot cycle with cryogenic heat sinks. The predicted system mass is 3.1 kg, to provide 64 mW of cooling at 2.3 K. The operation of the reversible circulator module at prototypical operating conditions has been demonstrated. These early research efforts show that the AMRR system is an attractive cooler for NASA's future advanced infrared, X-ray and gamma-ray detectors.

ACKNOWLEDGMENTS

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