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Development of an active magnetic regenerator for space applications

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A B S T R A C T

This paper discusses the design of a micromachined regenerator in an Active Magnetic Regenerative Refrigeration (AMRR) system for space applications. The AMRR system is designed to provide continuous remote/distributed cooling at about 2 K and reject heat at temperatures of about 15 K. This paper first discusses the general thermal and fluid performance requirements for an AMRR regenerator, a unique structured bed configuration that enables the regenerator to meet these requirements, and its thermal and fluid performance based on numerical analyses. The paper then discusses the general design consideration for the magnetic field driving the regenerator for optimal thermal performance, and the analysis processes to optimize the variation rate of the magnetic field in an actual superconducting magnet during the isothermal processes of the AMRR cycle to enhance the performance of an actual regenerator. The paper finally presents the thermal performance of the regenerator from such iterative design optimization processes.

1. Introduction

An Active Magnetic Regenerative Refrigeration (AMRR) system is a magnetic cooler utilizing a regenerative process that lifts heat from low temperatures to relatively high temperatures. The circulating fluid in an AMRR enables the cooler to provide remote, distributed cooling to payloads. These performance features, along with its ability to achieve much higher thermal efficiency than mechanical coolers, make it very attractive for providing cooling at about 2 K for space applications. For this reason, an AMRR system is being developed to assess its performance benefits for space applications.

An AMRR system mainly consists of two identical magnetic regenerators surrounded by their superconducting magnets and a reversible circulator, as shown in Fig. 1. Each regenerator also 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—one regenerator is being magnetized while the other one is being demagnetized. The circulator controls the flow direction, which cycles in concert with the magnetic fields to facilitate heat transfer. 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, absorbs heat from the refrigerant, and enters the hot end heat exchanger to reject the magnetization heat. The system is designed to provide a gross cooling power of about 50 mW at 2.3 K using the most common magnetic refrigerant Gadolinium Gallium Garnet (GGG). Heat from the regenerators and the circulator are rejected to a 15 K heat sink and a 30 K heat sink, respectively. The circulator is a centrifugal bidirectional pump using self-acting gas bearings to achieve vibration-free operation.

Subcritical ^{3}He with a pressure slightly below its saturation pressure corresponding to the AMRR cold end temperature is used as the circulating fluid. A nominal cycle period of 10 s is selected in the current design. Reducing the cycle period will proportionally increase the system cooling capacity. The minimal cycle period, however, is limited by three considerations: (1) the efficient operation of the reversible circulator associated with the flow switching process, (2) the minimum ratio of ^{3}He shuttle volume during half-cycle to the regenerator void volume; this ratio needs to be larger than 1 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 superconducting magnets and their driving circuit. These considerations led to the selection of a cycle period of 10 s.

Because the mass of the high-speed rotor in the centrifugal circulator is very small, about 1 g, it is expected that the flow direction switching can be implemented within one second, a small fraction of the cycle period. For this reason, in this preliminary design analysis, a perfect square wave is assumed for the helium flow rate during the isothermal processes. In practice, there is a

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Nomenclature

f	friction factor	Q	heat energy
F_M	figure of merit	Pr	Prandtl number
GGG	Gadolinium Gallium Garnet	Re	Reynolds number
H	magnetic field strength	s	entropy
j	Colburn factor	μ_o	magnetic permeability of space
Nu	Nusselt number		

very short transient process to stop the circulation flow rate and to raise the flow rate in the reverse direction. The transient process will very slightly reduce the net cooling power of the AMRR.

The operating temperature of the superconducting magnets is the same as the regenerator warm end temperature (~15 K). This enables the superconducting magnets to operate at its maximum design field strength right after the magnets are cooled down to their operating temperature by the upper stage mechanical cryocooler, enabling the AMRR to produce cooling power to gradually cool down the cold end of the regenerator and the payload. The cooldown process is analogous to that of a regenerative mechanical cryocooler.

The development of an AMRR requires three key technologies: (1) a reversible, vibration-free cryogenic circulator; (2) active magnetic regenerators; and (3) high-temperature, high-field-strength superconducting magnets. The overall AMRR system design, including the selection of key system operating parameters, such as circulation fluid, system pressure, and cycle period was discussed in an earlier paper [2]. This paper will discuss design and analysis of the regenerator.

The design analysis effort reported in this paper is built on many research efforts in this area [8,5], especially the work at MIT led by Joe Smith [9,4,7]. The development effort reported here takes advantage of recent advances in microfabrication techniques to build a microchannel regenerator with an anisotropic structured bed to enhance thermal performance. The analysis effort also developed a practical design process to optimize the magnetic field profile and circulating fluid flow rate to maximize the regenerator performance.

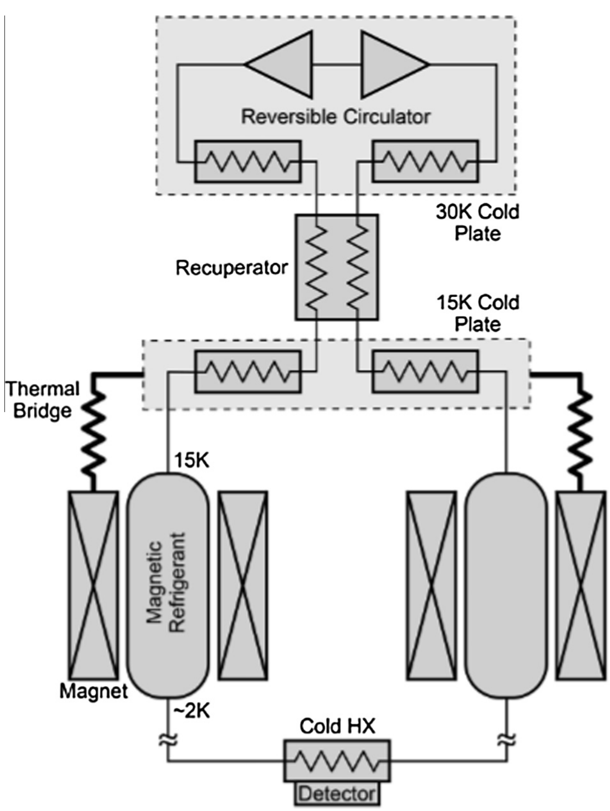

Fig. 1. System schematic of an AMRR with a reversible circulator. The AMRR cycle period is 10 s, the maximum magnetic field is 5 T and nominal cooling power is about 35 mow. Low-pressure ^{3}He is used as the circulating fluid. The flow direction reverses every half-cycle.

2. Design requirements for AMRR regenerator

An active magnetic regenerator is a regenerative heat exchanger with its matrix material made of 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).

To serve these functions effectively, the circulating fluid in the regenerators must be able to effectively transfer heat with the magnetic refrigerant matrix. In addition, the regenerators must also have the following characteristics for high performance:

1. Low axial conduction heat leak to reduce the parasitic heat flow from its hot end to its cold end.
2. A low flow resistance to reduce pumping work by the cryogenic circulator.
3. A small void volume to reduce the size of the regenerator and thus the size and mass of the superconducting magnets and their shields. It will also reduce the amount of ^{3}He in the regenerator. ^{3}He in the void volume will reduce the magnetic refrigerant's temperature swing during the "adiabatic" magnetization and demagnetization processes, preventing the process from approaching an isentropic process and resulting in a lower system performance.
4. A robust structure to withstand launch vibrations. Single-crystal GGG is a brittle material. GGG plates in a structured bed must be properly supported to prevent potential fracture failure.

Meeting all these performance requirements is very challenging. Simple conventional packed bed magnetic regenerators cannot meet these requirements. 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. A packed bed with small GGG beads will have an unacceptably large axial conduction heat leak. Thermal