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1-D transient numerical model of a regenerator in a novel sub Kelvin Active Magnetic Regenerative Refrigerator

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ABSTRACT

A sub Kelvin Active Magnetic Regenerative Refrigerator (AMRR) is being developed at the University of Wisconsin – Madison. This AMRR consists of two circulators, two regenerators, one superleak, one cold heat exchanger, and two warm heat exchangers. The circulators are novel non-moving part pumps that reciprocate a superfluid mixture of $^4He–^3He$ in the system. Heat from the mixture is removed within the two regenerators of this tandem system. An accurate model of the regenerators in this AMRR is necessary in order to predict the performance of these components, which in turn helps predicting the overall performance of the AMRR system. This work presents modeling methodology along with results from a 1-D transient numerical model of the regenerators of an AMRR capable of removing 2.5 mW at 850 mK at cyclic steady state.

1. Introduction

Development of a novel sub Kelvin Active Magnetic Regenerative Refrigerator (AMRR) is discussed in this work. This system will be able to distribute cooling over large shields or surfaces of space science components. Specifically to shield parasitic radiation heat load form the surroundings onto sensitive space science detectors in the micro to gamma wave. This system has unique advantages over conventional superfluid helium cryogen tanks used as cooling stabilizers. Among these are continuous operation, control over the cooling cycle and no mechanical moving parts. Also the AMRR discussed in this work is a suitable candidate to replace existing coolers in the low temperature range in order to couple ultra-low temperature coolers with higher temperature cooling stages such as those developed by Shirron [1] and Zagarola [2] respectively. The objective of this section is to familiarize the reader with the foundational concepts underlying the AMRR system.

The driving mechanism for magnetic coolers is the magneto-caloric effect. A paramagnetic material such as Gadolinium Gallium Garnet ($Gd_3Ga_5O_{12}$ or GGG) exhibits magneto-caloric effect; the magnetic dipoles are initially randomly oriented. When a magnetic field is applied to the material, its dipoles start aligning with the field, therefore the magnetic entropy (magnetic contribution to entropy) decreases. The total entropy of the material must be conserved during an adiabatic process. Therefore the thermal entropy (thermal contribution to entropy), hence temperature increases. Once the magnetic field is adiabatically removed, the dipoles are randomly oriented and the material once again returns to its original state. In order to cool an object, heat is rejected isothermally during magnetization, followed by an adiabatic demagnetization. The material then absorbs heat until it reaches its initial thermodynamic state [3].

Our AMRR shown in Fig. 1 uses a liquid mixture of $^3He–^4He$ as its heat transfer fluid, and GGG as its refrigerant. The key components in our AMRR are a thermodynamically reversible circulation device and a magnetic regenerator. Our AMRR will not need to use a heat switch, and will be able to provide continuous cooling with no moving mechanical parts. Our AMRR is a tandem system; two refrigerators that operate half cycle apart from each other. A tandem system of this type doubles refrigeration capacity and provides easier displacer mechanism from a control standpoint. Our system will have the advantage of providing the necessary cooling to large shields and surfaces and the magnets can be positioned remotely from the sensitive measurement devices that would induce an adverse effect otherwise. A more detailed conceptual description of the circulator technology and AMRR were discussed elsewhere by the authors of this work [4,5].

A model of each component of the AMRR accompanies the discussion of the apparatus in this work. The purpose of presenting these models is to quantify the design parameters of the system and to fill the gap in connecting each component to one another from a design standpoint. Therefore, the novelty of this system stems from the two key components of this refrigeration system

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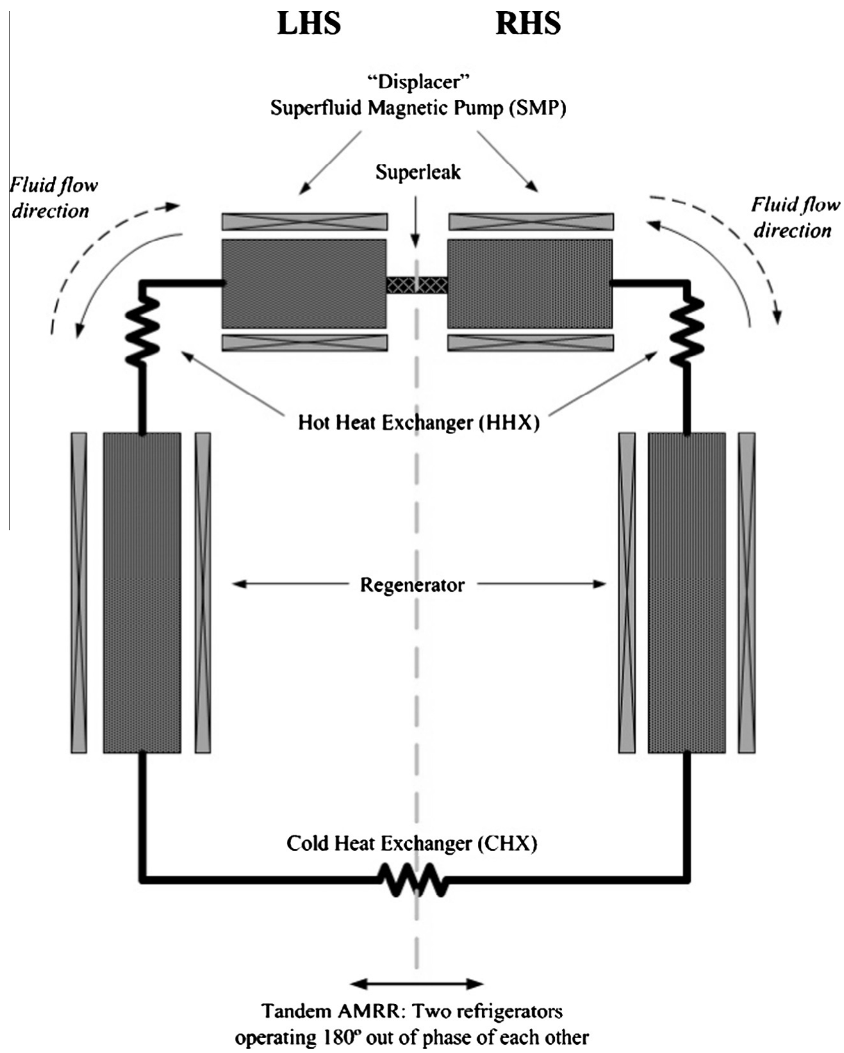

Fig. 1. A schematic view of our AMRR system.

and their functionality in conjunction with other components of the system: the Superfluid Magnetic Pump (SMP), and the regenerators.

2. System description

The AMRR consists of five major subcomponents: two SMPs, one superleak, two regenerators, two hot heat exchangers, and one cold heat exchanger. The SMPs and regenerators are similar in construction; they are made out of metallic canisters (Stainless Steel 304) filled with crushed GGG particles where the void is filled with a liquid mixture of ^{3}He–^{4}He. The canisters are surrounded by superconducting magnets and suspended via Kevlar strings, making them thermally isolated from the external environment as shown in Fig. 2. The superleaks, located between the two SMPs, are cylindrical Vycor® glass that becomes permeable only to superfluid ^{4}He during operation of the SMP. The hot heat exchanger is anchored to a 1 K platform (nominal temperature of 1 K) while the cold heat exchanger at the bottom of the system absorbs the heat load to be removed.

2.1. Cycle operation

For the operation description consider the Left Hand Side (LHS) of the system shown in Fig. 1. Only one half of the system can be considered from a modeling and description standpoint for two primary reasons: The two halves operate identically only one half is 180° out of phase from the other half, and the superleak and cold heat exchanger are considered as appropriate "breakpoints" for the two halves to be linked through the model. This is because only superfluid ^{4}He can travel through the superleak from one half to the other without affecting the other variables (superfluid carries no entropy). The cold heat exchanger "marries" the two halves in the modeling by considering a finite temperature rise through the cold heat exchanger once the helium mixture absorbs heat from a specimen. Every other part in between including the regenerators can be considered independent from one another since there is no direct heat exchange between the two regenerators. One cycle consists of the four following processes, presented chronologically beginning with the No-flow Demagnetization process:

2.1.1. No-Flow Demagnetization (NFD)

The LHS SMP's temperature and applied field are held constant at $T_{SMP,low}$ and $B_{SMP,low}$ throughout this process; consequently, no flow is produced. The concentration of the mixture in the LHS SMP is at its highest within the SMP system. Initially, a temperature profile exists between the top and bottom of the regenerator. Demagnetization of the LHS regenerator begins by lowering the applied magnetic field from the peak field, $B_{Reg,peak}$. This process continues until the temperature at the bottom of the regenerator