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HYBRID STIRLING / REVERSE BRAYTON AND MULTI-STAGE BRAYTON CRYOCOOLERS FOR SPACE APPLICATIONS

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ABSTRACT

Space infrared (IR) sensor applications place demanding requirements on the cryogenic cooling system. These systems must typically have 8+ year life and very high reliability, typically >0.95 at eight years. This has been achieved by several companies, including Raytheon with Stirling-class machines and by Creare with reverse turbo Brayton (RTB) devices. Other requirements virtually always present for space cryocoolers include low mass, high efficiency, and low vibration output. For typical space infrared sensor cryogenic cooling applications, existing Stirling-class cryocoolers (which includes pulse tubes) excel relative to the RTB with respect to mass and often efficiency, but the RTB exports much less vibration. An additional requirement sometimes present for a given payload is that the refrigeration must be provided remotely, perhaps several meters from the ambient environment where the cryocooler machinery typically resides and to which the waste heat must be rejected. A Stirling-class machine cannot meet this last requirement unless it is coupled with a single- or two-phase pumped loop, a cryogenic heat pipe, or a recirculating cooling system. One approach is to combine a Stirling-class machine with a Joule-Thomson (JT) cooling system. Another approach, one that embodies important reliability and integration benefits, is to combine a Stirling-class cryocooler with a RTB cryocooler. The case study results for a particular Stirling-Brayton hybrid system are presented, along with a discussion of its integration characteristics. Such a hybrid system, if properly designed, accentuates the advantages and mitigates the weaknesses of the individual technologies. Finally, the hybrid approach is compared to a straightforward multi-stage RTB cryocooler.

KEYWORDS: Stirling, pulse tube, turbo Brayton, hybrid, astrophysics

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INTRODUCTION

The majority of space cryocooler applications and those of primary interest for the authors involve the thermal conditioning of infrared sensors. Refrigeration temperatures typically range from about 10 K for silicon-doped focal plane arrays to around 120 K for long-wave optics. The cryogenic operating temperature may be provided either through active or passive means. As mechanical cryocooler technology has matured, more and more such sensor systems are using active cryocoolers instead of passive cryogenic systems, such as cryogenic radiators and Dewar systems, which had dominated up until recent years. Indicative of this trend towards mechanical coolers, recent papers describe their widespread use for NASA [1] and the United States Air Force interest in space cryocooler development [2].

Mechanical cryocoolers provide numerous advantages over competing passive approaches. Cryocoolers are of significantly lower mass than cryogenic Dewar systems of comparable capacity. Cryocoolers also provide much longer life than Dewar systems, which must rely upon a finite source of either stored cryogen or high pressure gas that must in turn be expanded through a throttling orifice to create cooling. Cryocoolers are also typically lower in mass than cryogenic radiators (often called "cryoradiators"), and unlike cryoradiators, they do not require complex spacecraft maneuvers to assure one side of the spacecraft maintains deep space pointing. The mass advantage of mechanical cryocoolers over cryoradiators is particularly pronounced at low temperatures where the fourth order dependency of radiated emissive power (Q_{rad}) on temperature, i.e.,

$$Q_{rad} = \varepsilon A \sigma F T^4 \tag{1}$$

necessitates radiators of very large surface area to achieve appreciable refrigeration capacity (ε = emissivity, A = surface area, σ = Stefan-Boltzman constant, F = shape factor, and T is temperature). It is primarily for these reasons, low mass and long life, that cryocoolers have become the norm for modern cryogenic space sensor designs.

For longer wavelength applications, say >10 microns, the optics must typically be cooled in addition to the focal plane assembly (FPA) to reduce background radiative flux on the FPA and thus achieve the required sensitivity in the bandwidth of interest. A technologically straightforward approach is to use separate cryocoolers operating at distinct temperatures, one to cool the FPA and a second, operating at a warmer but still cryogenic temperature, to cool the optics. Another approach is to use a single multi-stage cryocooler. The goal of providing simultaneous FPA and optics cooling with a single cooler has driven the development of a variety multi-stage cryocoolers intended for space applications [3,4]. The optimization of multi-stage coolers was discussed in a recent paper by Kirkconnell and Price [5].

Multistage Stirling-class cryocoolers, which in this context includes Stirling, pulse tube, and combination Stirling / pulse tube systems, are characterized by compact size and high efficiency. These characteristics primarily arise from the compactness of regenerative heat exchangers and the inherent efficiency of the thermodynamic cycle upon which they operate. The moving components within the linear compressors that drive these systems, and in the case of the Stirling the displacer assembly as well, give rise to vibration that is exported to the supporting payload structure. Though attenuation to < 0.1 N has been achieved on Raytheon Stirling cryocoolers through active vibration cancellation techniques, Stirling-class cryocoolers still export considerably more vibration than is acceptable for some sensor systems. Reverse turbo Brayton (RTB) cryocoolers provide a very low vibration alternative. RTB cryocoolers utilize miniature turbomachines to produce refrigeration with almost imperceptible exported vibration. However, RTB cryocoolers are generally larger, heavier, and less efficient at the temperatures and loads of interest given current recuperator technology.

Recently, Raytheon and Creare have collaborated on the conceptual design of a particular three-stage hybrid cryocooler system that uses a Stirling class cryocooler to provide cooling for the upper two stages and a RTB cryocooler for the coldest stage. This approach was selected to optimally meet the thermodynamic and mass objectives and to satisfy the additional requirement for remote cooling. This design is described in the next section. The hybrid cooler description is followed by a discussion of how the same requirements set might be met, albeit less optimally, with a multistage RTB. Finally, we conclude with a discussion of the ongoing development of a flight-design, prototype multistage RTB cryocooler.

HYBRID STIRLING / PULSE TUBE / BRAYTON CRYOCOOLER SYSTEM

Raytheon and Creare recently completed the conceptual design of a hybrid cryocooler system intended for NASA astrophysics payloads requiring long life, high efficiency, low vibration, and remote cooling (FIGURE 1). The selected approach utilizes a two-stage, Stirling-pulse tube cryocooler (RSP2) in conjunction with a reverse turbo Brayton (RTB) cryocooler to provide refrigeration at 15 K, 25 K, and 75 K. Temperatures down to 4 K are attainable by this approach, but higher temperatures were of interest for the present effort. The RSP2 represents the latest in Stirling-class cryocooler technology from Raytheon [3]. The Creare RTB cryocooler is of direct heritage to the Near Infrared Camera and Multiple Object Spectrometer (NICMOS) Cryocooler System (NCS) currently flying on the Hubble Space Telescope [6]. The upper stage of the RSP2 provides 2 W net cooling at 75 K. The second stage of the RSP2 delivers 150 mW net refrigeration at 25 K and provides pre-cooling for the 15 K stage. The RTB cryocooler delivers 20 mW at the 15 K (coldest) stage and provides a means to deliver cooling to a remote 25 K load.

The conceptual layout shown is simply one example of how these components may be configured. The optimum integration scheme will be payload design dependent. The use of remote cryogenic thermal transport technology, the inherent capability of the RTB loop to "pipe" refrigeration, and the flexibility in orienting the RSP2 pulse tube cold tip at almost any angle with respect to the expander motor drive axis yields a system that can easily be tailored to meet a broad range of payload integration requirements.

A functional schematic is provided in FIGURE 2. The upper stage intercepts cryogenic thermal loads at a higher temperature to improve overall thermal subsystem efficiency. The RTB provides the required separation between the RSP2 second stage and the remote 15 K and 25 K interfaces. The RSP2 and RTB are independently temperature controlled through closed-loop circuits that use temperature sensors mounted as shown. In addition to temperature control, the Integrated Cryocooler Electronics Module (ICEM) supplies drive power to the turbomachines and RSP2 linear motors and provides active vibration control for the RSP2. The RTB produces virtually imperceptible vibrations and thus does not require active vibration control. The ICEM is essentially a repackaging of existing Stirling-class and RTB cryocooler control electronics into a single box.

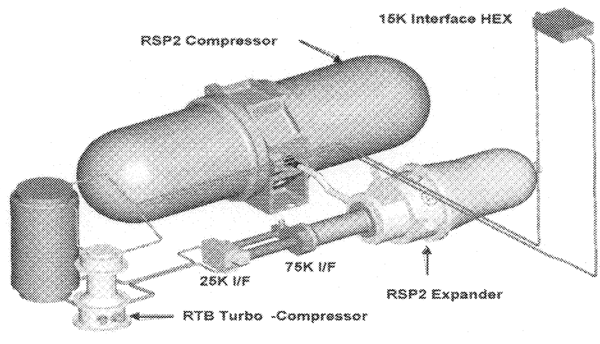

FIGURE 1. Raytheon / Creare Cryocooler System for Astrophysics. Refrigeration provided at 75 K and 25 K by the RSP2 and at 15K by the RTB. The 15 K and 25 K cryogenic interfaces can be located several meters from the other components to provide remote cooling.

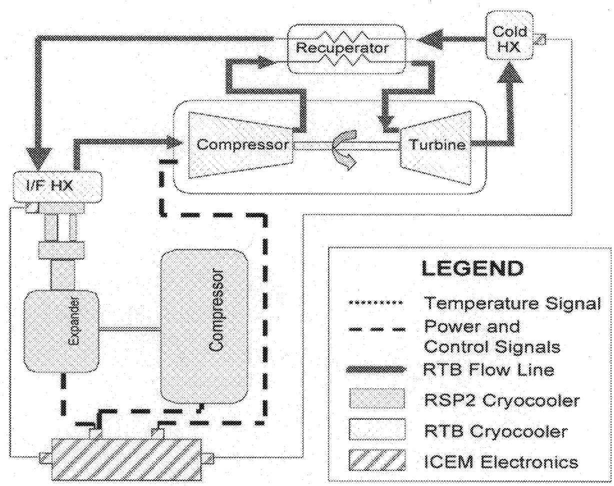

FIGURE 2. Hybrid Cryocooler System Functional Block Diagram.

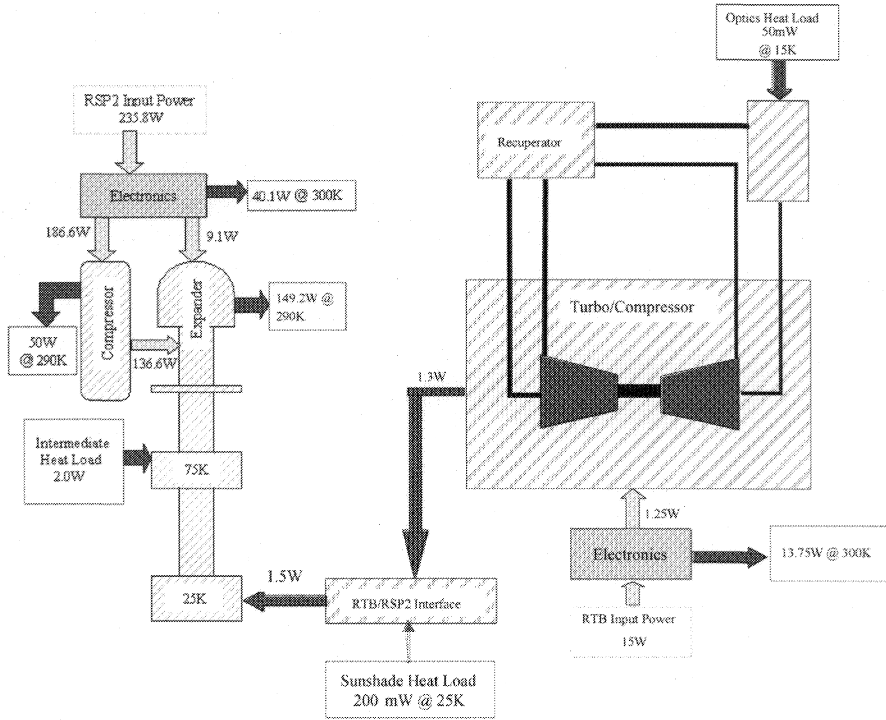

FIGURE 3. Cryocooler System Energy Flow Map. Design includes margin at the 15K (50 mW vs. 15 mW required) and 25K (200 mW vs. 150 mW required) reservoirs.

FIGURE 3 illustrates the thermodynamic performance and energy flows of the system. The RSP2 essentially serves as a heat sink for the RTB loop. The required RSP2 second stage capacity is thus the sum of the required net capacity at 25 K and the RTB heat rejection load on the RSP2. Additionally, the RSP2 produces 2.0 W at 75 K, which is available to cool a thermal shield. The total required system input power is 250.8 W.

Temperature and vibration control electronics and software are legacy to previous Raytheon and Creare designs. RSP2 temperature control is implemented with a digitally emulated PID controller. RSP2 compressor and expander vibration control is accomplished using Adaptive Feed Forward (AFF) controllers. RTB temperature control is provided through speed adjustment of the compressor rotor, as it is for NICMOS.

The estimated mass of this hybrid cryocooler system is 21.2 kg. The RSP2 accounts for 12 kg of that total, the ICEM is 6 kg, and the RTB turbo-compressor and recuperator are a combined 3.2 kg. This highlights another desirable feature of this configuration, which is the low mass of the components that must reside at the 25 K and 15 K stages.

The strengths of the proposed system are high efficiency, low vibration, easy start up, compact size, low mass, and inherent capability to provide remote cooling. The high efficiency RSP2 provides pre-cooling for the RTB, which improves the overall efficiency of the system. The RTB active components are carefully balanced turbomachines that produce essentially imperceptible vibration output, while the RSP2 employs Raytheon's proven vibration cancellation technology for linear coolers. The continuous flow nature of the Brayton cycle permits remote and/or distributed cooling, which in turn provides mechanical isolation from the low-level vibrations produced by the RSP2. Unlike a helium Joule-Thomson (J-T) system that necessitates pre-cooling of the helium below its inversion temperature of 40 K before it can produce refrigeration, the RTB produces cooling from ambient down below 6 K without complication. The result of all this is a highly efficient hybrid cooling system that transmits negligible vibration and permits distributed and/or remote cooling without the start up complexities of a JT-cycle.

MULTISTAGE RTB CRYOCOOLERS

An alternative approach to the hybrid cryocooler would be to use a multi-stage RTB cryocooler. For an application with a 15 K to 25 K primary load temperature and without a cryoradiator, a three-stage version would be required for high efficiency. A layout of this RTB cryocooler is shown in FIGURE 4. Two centrifugal compressors are located at the warm end of the system and produce the pressure ratio that circulates the cycle gas (helium). The compressors are driven by three-phase AC inverters (not shown) which are powered from an unregulated DC bus. The heat of compression is removed by an aftercooler, which is integral to each compressor body. The heat of compression and any compressor inefficiencies are rejected at the warm heat sink. The three turbines are plumbed in parallel and operate at the two primary load temperatures of 25 K and 15 K as well as an intermediate temperature of 70-100 K. Each turbine expands gas from high to low pressure producing shaft work that is converted to electrical power in an alternator (i.e. turboalternator). The electrical power is recovered or dissipated in the electronics at the warm end of the cryocooler. In order to improve cycle efficiency, recuperative heat exchangers (i.e. recuperators) are used to pre-cool the high-pressure stream using the colder low-pressure stream returning from the turbines. Small interface heat exchangers (IFHX) are used to cool each load. Multiple IFHXs can be used at each load temperature to cool multiple or remote loads.

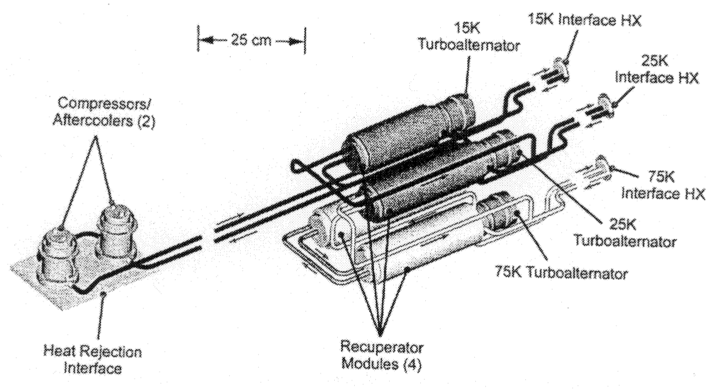

FIGURE 4. Three-Stage Turbo-Brayton Cryocooler. The cooler simultaneously provides 2 W of net cooling at 75 K, 150 mW at 25 K and 20 mW at 15 K, with margin.

The mass of the 3-stage RTB cryocooler is estimated to be 30 kg including electronics. This estimate was attained by sizing the recuperators such that the same total system power is achieved as for the hybrid cryocooler (250 W). To add fidelity to the estimate, the calculation was based on current component technologies that have heritage in the NICMOS Cryocooler or a later program and have been demonstrated at the intended operating conditions.

The Brayton cycle is most efficient at low pressure ratios (e.g. coefficient of performances approaches the Carnot cycle at pressure ratios approaching unity), and efficiency is even more critical for low temperature applications where the cryocooler input power is already large due to basic thermodynamics. A byproduct of operating at low pressure ratios is the need for relatively high flow rates, which has a significant impact on the size and mass of the recuperator. Design optimization trades for RTB systems primarily focus on recuperator size (and mass) and system input power. The current state-of-the-art recuperator for Brayton cycle cryocoolers is the Creare slotted-plate heat exchanger (SPHX). The SPHX has been space qualified and extensively tested over a broad range of operating conditions, and it has demonstrated a thermal effectiveness of greater than 0.997 with a cold end temperature as low as 5 K. The performance of this recuperator, to our knowledge, is the highest measured for a Brayton cycle recuperator. Advanced recuperator technology is currently under development at Creare under the sponsorship and direction of Missile Defense Agency and the Air Force. The advanced recuperator is predicted to provide landmark reductions in the size and mass of RTB cryocoolers, but this technology is still several years from a maturity level to be considered for space flight programs. This will benefit both multistage RTB and hybrid RSP2/RTB cryocoolers.

The RTB provides the same thermodynamic performance as the previously-described hybrid cooler, but it weighs 30 kg, which is 42% more than the hybrid cryocooler (21.2 kg). The single-stage RTB cryocooler in the hybrid cryocooler operates at a small temperature difference (and ratio), which allows high cycle efficiency with only modest thermal requirements for the recuperator. The resulting RTB is compact and lightweight in addition to its inherent attributes of low vibration, high reliability, and ability to cool remote and/or distributed loads. When coupled to a state-of-the-art Stirling-class cryocooler, the hybrid system thus excels at meeting the requirements of many NASA astrophysics missions.

Multi-stage RTB Cryocooler Development Progress

Raytheon and Creare are pursuing the development of a two-stage neon RTB cryocooler on a technology demonstration program. A preliminary layout is shown in FIGURE 5. All components have heritage to the NICMOS cryocooler. The cryocooler is designed to provide 12.6 W of cooling at the first stage temperature of 100 K and 1.8 W at the second stage temperature of 65 K; the predicted total power is 420 W at a heat rejection temperature of 316 K. Other key requirements that have driven the design are negligible vibration, significant separation distances between thermal interfaces, and a lifetime of greater than 8 years.

To meet these cooling requirements, the first stage requires a slotted-plate recuperator approximately 22 inches in length, divided into two modules to meet packaging constraints. The temperature of the working gas is reduced from approximately 300 K to 200 K in the first module, and from 200 K to 100 K in the second module. The first-stage turbine and first-stage load interface heat exchanger are remotely mounted away from the first-stage recuperator. An additional turbine and recuperator are used to reduce the working gas temperature from the first-stage temperature of 100 K to 65 K. These components are mated into a single module

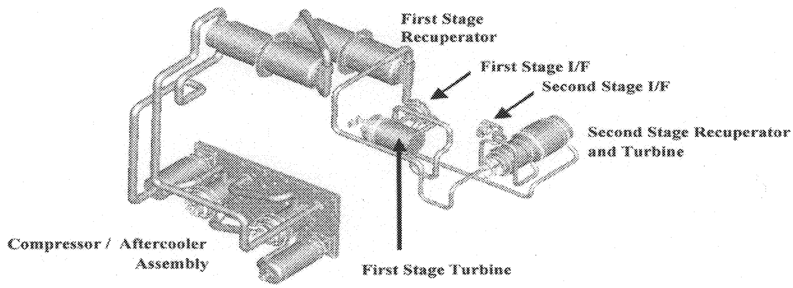

FIGURE 5. Layout of Creare / Raytheon Two-Stage RTB Cryocooler.

with a total length of 9 inches. The cooled working gas is routed a short distance from the turbine to the 65 K interface heat exchanger. The compressor/aftercooler is mounted remotely to the heat sink to minimize the thermal parasitic heat loads on the cryocooler and improve the efficiency of waste heat rejection.

The cryocooler electronics development involves Raytheon, Creare, and Jackson and Tull Chartered Engineers. The electronics design for the system arises from a combination of NCS heritage brought by Jackson and Tull, Creare's patented rotating filed inverter (RFI) drive circuits, and Raytheon's modular flight electronics packaging techniques.

CONCLUSION

A hybrid, multistage cryocooler conceptual design has been developed that combines Raytheon's Stirling-class technology with Creare's RTB technology. This combination is particularly advantageous for astrophysics missions in which high thermodynamic efficiency, remote cooling and low exported vibration are required. Creare and Raytheon are also developing a multistage RTB cryocooler for future missions.

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