

Raytheon High-Frequency Pulse Tube Cryocooler Testing

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ABSTRACT

Since the 1970s, Raytheon has developed, built, tested and integrated high performance cryocoolers. Our versatile designs for single and multi-stage cryocoolers provide reliable operation for temperatures from 10 to 200 kelvin with power levels ranging from 50 W to nearly 600 W. These cryocoolers incorporate clearance seals, flexure suspensions, hermetic housings and dynamic balancing to provide long service life and reliable operation in all relevant environments. Recently, Raytheon has developed an advanced regenerator technology capable of operating efficiently at high frequencies and outperforming traditional screen regenerators. The Raytheon Advanced Miniature (RAM-100) cryocooler, a flight packaged, high frequency, single stage pulse tube cooler with an integrated surge volume and inertance tube, has been designed for use with this regenerator. Design details and experimentally measured performance of two iterations of the RAM cryocooler are presented in this paper.

INTRODUCTION

Raytheon's Advanced Miniature (RAM) cryocooler was developed to provide the high reliability and thermodynamic efficiency typical of a space cryocooler with a lower cost and lead time than such systems have traditionally required [1]. This has been accomplished by emphasizing simplified and streamlined manufacturing processes in the RAM design. This approach is similar to that taken for the Raytheon Dual-Use Cryocooler (DUC) [2], but for the RAM design performance, robustness, and ease of integration were prioritized above pure ease of manufacturing. Additionally, the RAM cooler was developed to take advantage of the systematic benefits of a high operating frequency. These include a reduction of lower frequency exported disturbance, to which space systems are often sensitive, and a decrease in the relative size and mass of cryocooler components.

When dealing with cryocooler exported disturbance, the higher operating frequency of the RAM compared to other similar capacity cryocoolers results in several benefits for a systems integrator. First, the increased fundamental frequency results in fewer harmonics in the frequency range where structures and instruments are typically sensitive to disturbances. Additionally, soft-mount isolation systems are generally more effective at attenuating vibration as the source frequency increases. With a higher frequency source, these soft-mounts can be made stiffer for the same attenuation roll-off, resulting in more survivable soft-mounts and possibly eliminating the need for launch-locks.

To date, Raytheon has built and tested two flight-capable RAM Thermo-Mechanical Units (TMUs) that are able to operate between 90 and 100 Hz and deliver these operational benefits. They incorporate the Raytheon advanced regenerator [3], which has the potential to outperform

traditional regenerators in this frequency range, and have undergone extensive analysis during the design to ensure that they are robust and reliable.

MECHANICAL DESIGN AND SPECIFICATIONS

The RAM cryocooler is a split pulse tube design as shown in the photograph of Figure 1. The compressor is an Oxford-style design featuring dual opposed pistons for dynamic balancing, linear motors, a flexure suspension and non-contacting clearance seals. The expander module incorporates a concentric pulse tube and regenerator and an integrated surge volume and inertance tube. Additional aspects of both module designs are discussed in the paragraphs below.

The compressor architecture of the RAM cryocooler draws upon several recent design efforts, including the Low Temperature Raytheon Stirling/Pulse Tube hybrid (LT-RSP2) production compressor [4]. The RAM compressor incorporates clearance gap seals and flexure suspended moving mechanisms similar to other Raytheon space cryocoolers, but does away with piston position sensors in order to minimize package size and electronics complexity. Instead, piston position sensing and centering is performed using a technique based on the back-EMF of the motors.

The thermal, structural, and electrical interfaces of the compressor have been designed to simplify integration of the RAM cryocooler into an objective system. Heat rejection is accomplished through a single flange perpendicular to the mounting interface, which greatly simplifies attachment of heat pipes or thermal straps. The housing design allows simple three bolt mounting and incorporation of load washers while the RAM electronics are capable of utilizing either load washers or chassis-mounted accelerometers for vibration control feedback, allowing flexibility depending on the integration requirements. Industry standard connectors are installed for straightforward power and telemetry wiring. For robustness every sealed interface, with the exception of the transfer-line connecting the compressor and expander, is hermetically welded to eliminate the potential for leaks through handling or radiation exposure.

The RAM expander also incorporates a number of manufacturing and thermodynamic improvements, capitalizing on several years of Raytheon IRAD advancements. The cold-end tip incorporates two flat mounting interfaces, creating predictable, consistent thermal-strap and instrumentation conduction paths. Heat rejection is accomplished through either or both of the expander body sides, which incorporate bolt patterns for direct connection of heat pipes or thermal straps. The seamless design of the expander includes no external tubing or joints for inertance tube/surge volume attachments and the expander is designed to be mounted using a built-in vacuum interface, ensuring easy integration with instrument dewar structures.

Unit production and assembly of the RAM TMU is straight-forward and efficient, minimizing unnecessary critical path steps. Fabrication of the initial unit was completed very quickly with assembly of the compressor module requiring less than a week, including all curing, bake-out, and



Figure 1. Photograph of RAM-100 Compressor and Expander.

Table 1. Comparison of RAM and DUC dimensions and masses

DUC TMU			RAM TMU		
Compressor		Expander	Compressor		Expander
Mass	3.9 kg	1.4 kg	Mass:	2.8 kg	0.9 kg
Package Size			Package Size		
Length:	8.2 in	5.4 in	Length:	7.9 in	6.3 in
Width:	4.5 in	4 in	Width:	3.75 in	3.4 in
Height:	4.5 in	4 in	Height:	3.75 in	3.4 in

alignment processes. In quantity production, assembly is expected to be completed in a single day for this compressor design. Initial checkout and acceptance procedures were also completed quickly and without incident. The expander module, was designed with a simplified braze/weld schedule, removing several manufacturing steps found in previously designed coolers; this resulted in a significant decrease in assembly time and reduction of critical-path supply risks.

Size and Mass

The increased operating frequency of the RAM cryocooler relative to its predecessor, the Raytheon DUC, resulted in reductions size and mass for both the compressor and expander modules. These reductions, totaling approximately 1.6 kg of mass, were accomplished while integrating thermal, electrical, and structural interfaces which were mostly not incorporated into the DUC design. The lone dimension to grow from the DUC to the RAM was the expander length, which increased due to the integration of the surge volume and inertance tube into the expander body.

Structural Analysis

Extensive structural analysis was performed during the development of the RAM cryocooler in order to ensure robustness and reliability. This included industry standard pressure vessel, modal, thermo-elastic, and radiation analyses as well as comprehensive random vibration, quasi-static loading, shock, and combined loading analyses. To guarantee that the RAM-100 would meet most future shock and vibration requirements, a 300 g inertial load was used for the purposes of verifying shock and as a bounding case on random vibration analysis. Any shock event will be strictly dependent on the particular system in which the event happens, however several design features of the RAM-100 compressor and expander result in a relative lack of susceptibility to a shock environment. The TMU components were also examined against a random vibration profile of .2 g²/Hz across all resonant frequencies. In all of these analysis cases, the compressor and expander of the RAM-100 cryocooler showed positive margins.

Electronics

The RAM cryocooler is designed for compatibility with the Raytheon Cryocooler Thermal Control Electronics (CTCE) as well as third party, tactical style cryocooler electronics.

MECHANICAL DESIGN AND SPECIFICATIONS

Initial thermodynamic characterization of the RAM cryocooler was completed in 2015, the results of which are shown in the Ross plot in Figure 2. This initial testing was performed at a 91 Hz operating frequency with a heat reject temperature of 295 K. Because the first planned application for the RAM cooler requires cooling at ~150 K, the first expander included a higher flow regenerator more suitable for warmer cold tip temperatures. As a result, the first RAM cooler performed well at cold tip temperatures of approximately 100 K and above but exhibited reduced performance at lower temperatures. The less restrictive regenerator likely also resulted in the observed reductions in the optimal operating frequency and maximum input power, both due to a reduction in the pressure ratio and resulting gas spring contribution to the compressor resonant frequency.

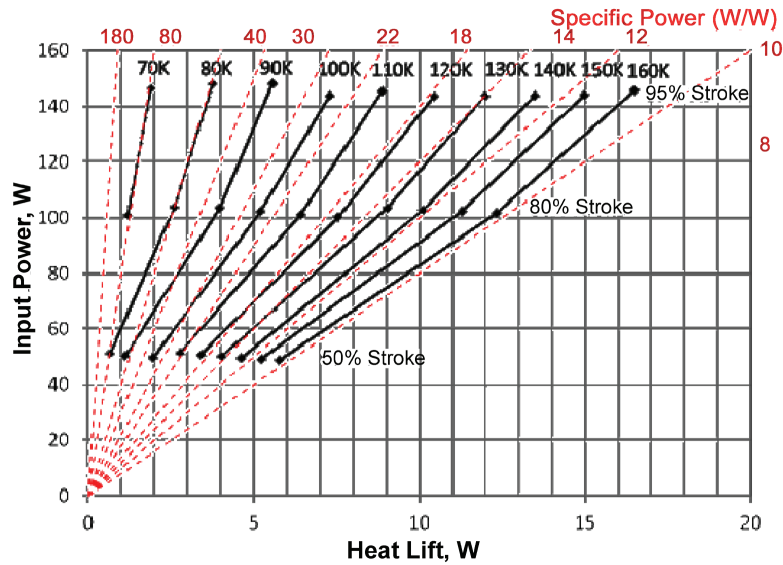


Figure 2. Ross plot for RAM cryocooler with regenerator optimized for cooling above 100 K.

A brassboard RAM expander has also been constructed which incorporates a regenerator optimized for lower temperature operation. Testing of this expander with a production RAM compressor was performed in early 2016; the results of this testing are shown as a Ross plot in Figure 3. This expander significantly outperformed the previous expander, which had been optimized for higher temperature operation, at temperatures below approximately 100 K and achieved a no-load temperature of 42 K. The brassboard testing was performed at an operating frequency of 100 Hz and a reject temperature of 300 K. A production version of this lower temperature expander, to be completed later this year, will incorporate the same design features, geometry, and robustness as the current unit; the only changes to be made are to the design parameters of the regenerator. Due

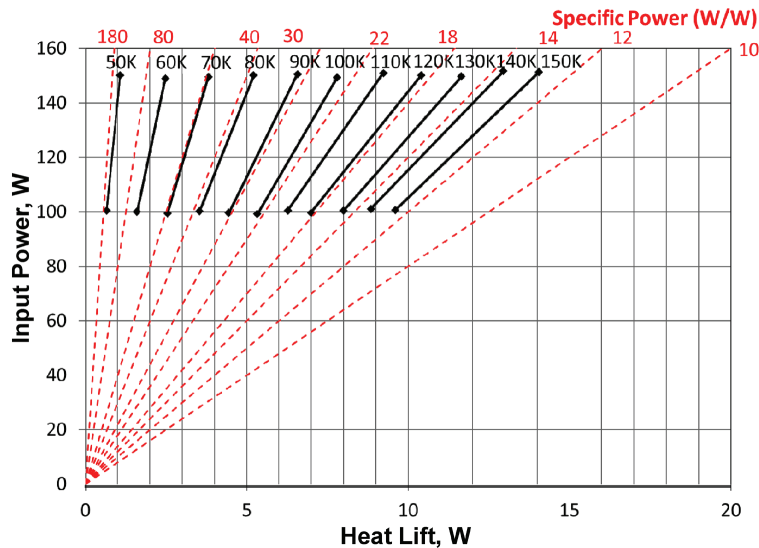


Figure 3. Ross plot for brassboard RAM cryocooler with regenerator optimized for cooling below 100 K.

to slight geometry differences between the brassboard and planned production unit, the production expander is predicted to operate optimally at 100 Hz.

CONCLUSIONS

The RAM cryocooler has been developed as a miniaturized, flight ready TMU capable of capitalizing on the system benefits of high frequency operation. It incorporates many legacy design features from other Raytheon space cryocoolers and has been designed with robustness, reliability, and ease of integration in mind. Initial testing of a production RAM cryocooler has been performed along with additional testing of a brassboard expander optimized for lower cold tip temperatures.

ACKNOWLEDGMENT

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