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ABSTRACT

The first generation flight-design Stirling / pulse tube "hybrid" two-stage cryocooler has entered initial performance and environmental testing. The status and early results of the testing are presented. Numerous improvements have been implemented as compared to the preceding brassboard versions to improve performance, extend life, and enhance launch survivability. This has largely been accomplished by incorporating successful flight-design features from the Raytheon Stirling one-stage cryocooler product line. These design improvements are described. In parallel with these mechanical cryocooler development efforts, a third generation electronics module is being developed that will support hybrid Stirling/pulse tube and Stirling cryocoolers. Improvements relative to the second generation design relate to improved radiation hardness, reduced parts count, and improved vibration cancellation capability. Progress on the electronics is also presented.

KEYWORDS: Cryocooler, space cryocooler, multistage, hybrid, Stirling, pulse tube, cryocooler electronics.

INTRODUCTION

Raytheon is developing hybrid Stirling / pulse tube cryocoolers to address the needs of the United States Government (USG) for two-stage cryocoolers, primarily to provide simultaneous optics and focal plane cooling for space-borne infrared sensors [1]. Raytheon has selected this unique hybrid combination of Stirling and pulse tube technologies for our two-stage cryocooler development campaign primarily because of the operational advantages it provides the user. This includes the capability to shift capacity between the stages at nearly constant input power and efficiency, broad setpoint flexibility, and a compact and robust cold finger. Details of the underlying technology and a chronicle of

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the development efforts is available through review of a series of papers, which trace all the way back to the invention of the hybrid Stirling / pulse tube in 1999 [3-7]. One will note that in recent years this type of cryocooler has come to be known by the acronym "RSP2" (**R**aytheon **S**tirling / **P**ulse Tube **2**-Stage Cryocooler).

This paper provides status on the overall RSP2 development effort. The discussion is brought forth in three parts, reflective of three separate (but related) development projects presently addressing the overall campaign. Thus there is a discussion on the Air Force Research Laboratory (AFRL)-sponsored High Capacity RSP2 (HC-RSP2), the Raytheon-funded Mid Capacity RSP2 (MC-RSP2), and the related next generation cryocooler electronics. As the names imply, the HC and MC are simply differently scaled versions of the same basic architecture. The electronics is modular and scaleable so it can support both. The focus of the paper is on the HC-RSP2, because it is leading the MC-RSP2 by about 3 months, and the development sequence is nearly identical.

HIGH CAPACITY RSP2 CRYOCOOLER

Program Overview and Objectives

The HC-RSP2 Program is managed by AFRL Space Vehicles Directorate, Kirtland Air Force Base, New Mexico. The objective of the program is to develop a high capacity, two-stage cryocooler to meet the needs of future payloads requiring large capacity relative to existing space cryocoolers. The top level performance and environmental requirements provided in TABLE 1 are intended to represent a "typical" requirements set for a cryocooler of this class.

In that same vein, the HC-RSP2 also has radiated emission requirements, as follows. The magnetic field shall be <146 dBpT at 30Hz decreasing linearly to < 76 dBpT at 100 kHz (50 cm distance). The electric field shall be <80 dBμV/meter over the 14 kHz to 18 GHz frequency range.

TABLE 1. HC-RSP2 Cryocooler Top Level Performance and Environmental Requirements

Description	Units	Requirement
2nd Stage Capacity	W	2.0
2nd Stage Temperature	K	35
1st Stage Capacity	W	18.0
1st Stage Temperature	K	85
TMU Input Power	W	< 500
Exported Vibration (0-500 Hz, 3 axes)	mN	< 200
2nd Stage Temperature Stability	K	+/- 0.25
Operational Temperature Range	K	250 - 300
Non-operational Temperature Range	K	200 - 320
Applied Vibration, total	grms	12.8
Applied Vibration, peak	g^2/Hz	0.1

Although future specific payload needs are at present undefined, the purpose here is to assure that the cryocooler developed can meet a wide range of projected mission needs, and that it can be flight qualified consistent with a "typical" requirements set. (It should be noted that the values provided in TABLE 1 do not represent the capability limit of the technology; alternative load and temperature combinations are available, as well as suitability to a more rigorous set of environmental requirements.)

Technical Description

The technical approach taken to meeting the aforementioned requirements is a Stirling / pulse tube hybrid two-stage cryocooler with a concentric second stage (pulse tube) cold finger. FIGURE 1 provides a solid model image of the HC-RSP2 Cryocooler. The compressor is a dual-opposed piston, reciprocating device, similar to previous Raytheon flight compressors [7] in most ways except capacity. The HC-RSP2 compressor is capable of over 20 cc total displacement, as compared to nominally 3 cc for the Raytheon Stirling One-Stage (RS1) Cryocooler. The underlying hybrid technology has been described previously [2-6]. In short, the first stage refrigeration is produced as in a conventional Oxford-class Stirling cryocooler. The expander piston is driven at a phase angle that leads the compressor pistons by nominally 90 degrees. The second stage expansion is provided in the usual way by an inertance tube / surge volume, although there are a number of means by which the inertance tube and surge volume may be implemented, as described below. A concentric arrangement was selected primarily to reduce cold finger mass, and by so doing increase the first structural mode above 400 Hz.

Risk Reduction Testing

Prior to configuring the unit into its final deliverable configuration, a number of tests were performed to screen for manufacturing and/or design defects at a lower level. This proved prudent. Initial testing of a brassboard version of the expander revealed that the regenerator clearance seal gap was too small, resulting in unacceptably large expander piston friction. The correct sizing was determined on the brassboard expander, so a fix was could be implemented on the flight-design expander prior to final integration.

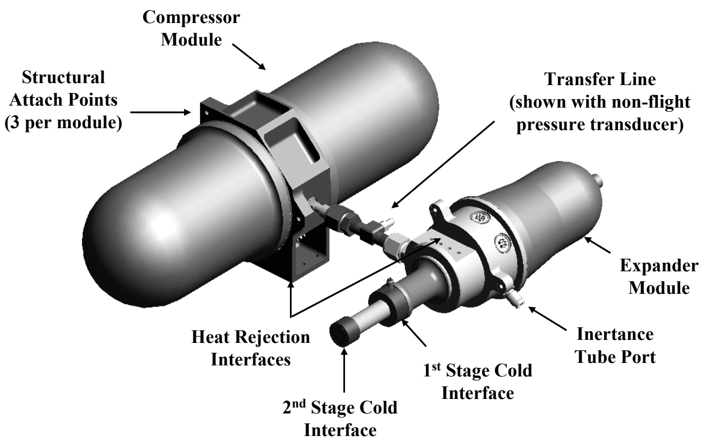

FIGURE 1. HC-RSP2 Cryocooler Solid Model. Critical integration features shown. Inertance tube and surge volume not shown.

An interesting series of cryocooler-level risk reduction (RR) tests utilizing an ambient temperature surge volume was recently completed. See FIGURE 2. The inertance tube was divided into two sections in series, the first connecting the first stage cold manifold to the dewar interface plate, and the second connecting from that point to the surge volume. For reasons described below, this is not the flight configuration, although it did prove convenient for a complete cryocooler demonstration and to provide data for model correlation.

The data from the RR testing are provided in FIGURE 3. Also shown are the predictions from the thermodynamic math model for these same operating points, with agreement typically within 2 K for a given heat load at either stage. Of note is that the Stirling mechanical phase angle (relative to the compressor pistons) in the model had to be increased by about 6 degrees to achieve the optimum agreement with the experimental data. This has been seen before in hybrid Stirling / pulse tubes, so this behavior was not unexpected, although it remains at present not fully understood. The cryocooler provided 10.0 W at 85 K simultaneous with 3.0 W at 35 K for 497 W input power. As shown in FIGURE 3, this agrees well with prediction, providing high confidence in achieving the performance shown in TABLE 1 once placed into the final configuration, as described in the next section. Additional test and model correlation points are shown displaying thermodynamic performance and model agreement within a range of the design point.

Flight Design (FD) HC-RSP2

The RR test results described in the previous section and the associated correlated model have been used to finalize on the inertance tube and surge volume designs for the flight-design HC-RSP2 that will be delivered to AFRL. The changes between the risk reduction configuration and deliverable configuration differ only with respect to the inertance tube and surge volume. The expander module, compressor module, transfer line, and orientation as defined by the fixture shown in FIGURE 2 will be identical.

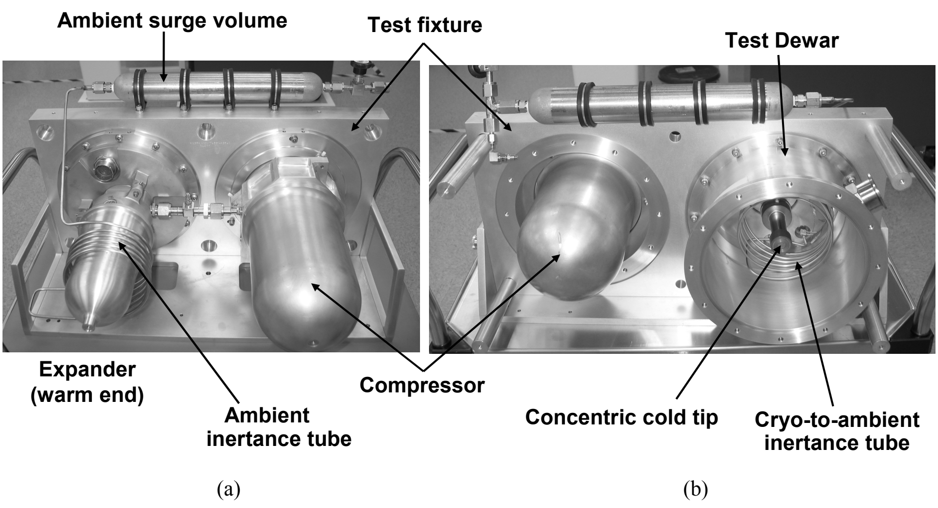

FIGURE 2. HC-RSP2 Cryocooler Risk Reduction (RR) Test. (a) Front and (b) rear views provided. "Cryo-to-ambient" section of inertance tube connects the pulse tube warm end heat exchanger, which is inside the first stage cold block, to the ambient inertance tube through a gas feedthru on the dewar interface plate.

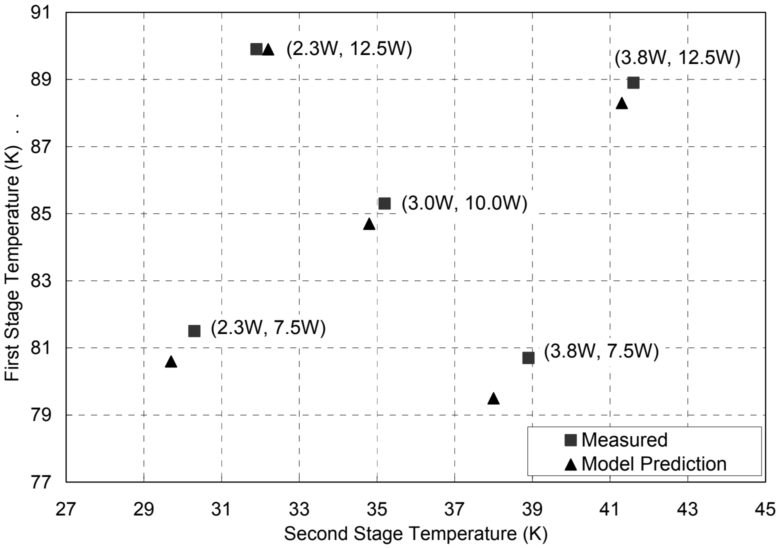

FIGURE 3. HC-RSP2 Risk Reduction Experimental Data. Correlated model predictions also provided to illustrate agreement between the model and the measured data. Heat lift at both stages provided in parentheses (stage 2 capacity, stage 1 capacity). Input power ~ 500 W for all points.

For the deliverable FD system, the ambient temperature surge volume and the inertance tube that connects it to the first stage manifold will be replaced with a cryogenic surge volume and shorter inertance tube that will both reside within the test dewar. Thus, instead of traversing from the nominally 85 K first stage temperature to ambient, the inertance tube will essentially be isothermal at the first stage temperature. This was done to achieve a 5X reduction in surge volume size, a 3X reduction in inertance tube length, and to improve thermodynamic performance. A shuttle loss occurs in the inertance tube that traverses from 85 K to ambient, directly reducing first stage capacity by approximately 2 to 3 W in this design. The previous baseline approach had been to use the expander plenum volume as the surge volume, but that only addresses the inertance tube and surge volume packaging issues, not the shuttle loss. The cryogenic surge volume approach shown in FIGURE 4 was therefore adopted.

The thermodynamic challenge in going from the RR to FD configurations is to shift the excess capacity from the second stage to the first stage ***and*** to increase the overall efficiency of the expander; load shifting alone is insufficient. Consider a comparison of a correlated model result for an operating point from the RR testing and a prediction for the FD design from a "normalized refrigeration" perspective (see TABLE 2). The total normalized refrigeration, following the method defined in an earlier paper [8], is given by:

$$Q_2^{'} = Q_2 + Q_1\left(\frac{\beta_{c,2}}{\beta_{c,1}}\right) \tag{1}$$

where $\beta_{c,x}$ is the Carnot efficiency as defined at each stage for $x = 1$ and $x = 2$:

$$\beta_{c,x} = \frac{T_x}{T_h - T_x} \tag{2}$$

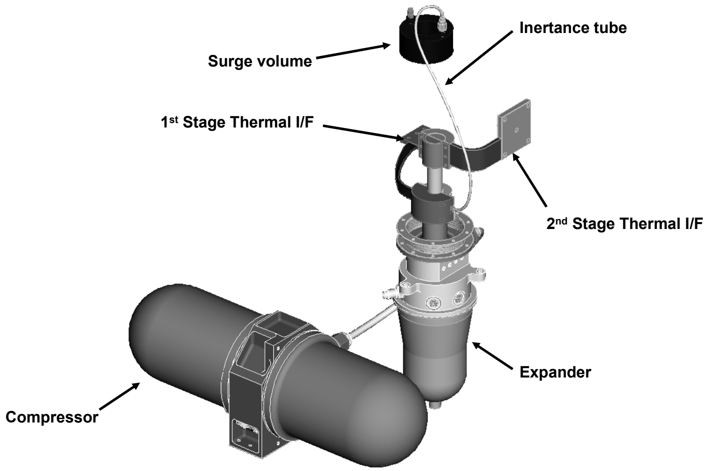

FIGURE 4. HC-RSP2 in Flight Design (FD) Configuration. Cryogenic surge volume would bolt to first stage object being cooled, such as the optical bench in a two-stage infrared sensor application.

T_h is the warm end rejection temperature, which is 300 K for all cases considered herein. As shown in TABLE 2, the normalized refrigeration must be increased by 1.79 W in going from RR to FD, or roughly 29%, for roughly the same or less input power.

As illustrated in TABLE 3, the required improvement can be achieved by simply replacing the RR inertance tube with a cryogenic inertance tube and re-optimizing the Stirling piston phase angle to shift capacity from the second stage to the first stage. Note that reducing stage 2 heat lift serves to increase stage 1 capacity because the second stage load passes to ambient through the first stage manifold. The net effect is obviously still a detriment to normalized capacity (0.32 – 0.96 = -0.64 W), which has been taken into account as shown. The calculated 1.81 W increase in normalized refrigeration agrees well with the known required 1.79 W increase from TABLE 2, providing additional confidence that the underlying physical mechanisms are well understood.

TABLE 2. HC-RSP2 Cryocooler Performance Comparison Between RR and FD. Units [watts].

	RR	FD	Net delta_Q2'
Wcomp	497	< 500	
Q2	2.96	2.00	
Q1	9.76	18.00	
Q2'	6.22	8.01	**1.79**

TABLE 3. Improvement in HC-RSP2 Performance from RR to FD. Units [watts].

RR to FD Improvement	Q [W]	Q2' [W]
- Stage 1		
Increase in gross capacity at Stage 1	+4.45	+1.49
Decreased Q2 load on Q1	+0.96	+0.32
IT shuttle loss elimination	+2.87	+0.96
- Stage 2		
Decreased Q2 heat lift	-0.96	-0.96
Net Q2' increase		+1.81

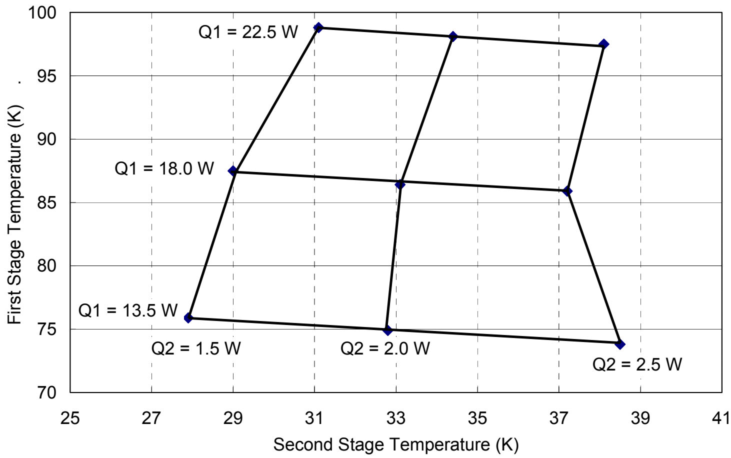

FIGURE 5. HC-RSP2 Load Map. Cryocooler input power ~ 475 W for all points shown. The values provided in the figure were determined using the correlated thermodynamic math model for the flight design (FD) with a cryogenic surge volume and inertance tube.

The predicted total cryocooler input power (compressor + expander) for the FD configuration is 471 W. The required refrigeration improvements were achieved within the power allocation with a 29 W margin. A complete load map is provided in FIGURE 5.

As has been discussed in previous papers [3-7], the unique staging of this particular hybrid cold head arrangement provides a partial coupling between the expansion phase angles. Commanded changes in the Stirling piston phase angle directly affect first stage capacity and indirectly affect second stage capacity. This provides the capability to shift capacity between the stages on command, and the load shift occurs at nominally constant input power because the drive frequency is held constant, allowing the cryocooler to continue to operate at resonance. Thus, a wide range of efficient operating points is available to the user, as shown in FIGURE 6.

RELATED EFFORTS AND SUMMARY

A "mid capacity" MC-RSP2 Cryocooler, developed on internal Raytheon funding, is proceeding in parallel with the HC-RSP2. It is basically a smaller version of the HC-RSP2, except that the cold head design was finalized before the HC-RSP2 development successfully demonstrated the concentric cold finger, so the unit features an earlier "U-tube" second stage design [3]. Future iterations of the MC-RSP2 will be built with a concentric cold finger to take advantage of the packaging and structural advantages.

The MC-RSP2 Cryocooler development has paralleled that of the HC-RSP2 in that initial testing was performed using an ambient temperature surge volume to determine the optimum inertance tube sizing. As with HC-RSP2, a cryogenic surge volume / inertance tube is being used for the flight design. The predicted performance of the MC-RSP2 at its design point is 2.7 W @ 58 K + 6.7 W @ 110 K for 210 W input power. Lessons learned from the HC-RSP2 Program, which started after MC-RSP2 but will finish first, are predicted to reduce input power to less than 175 W for those same heat loads.

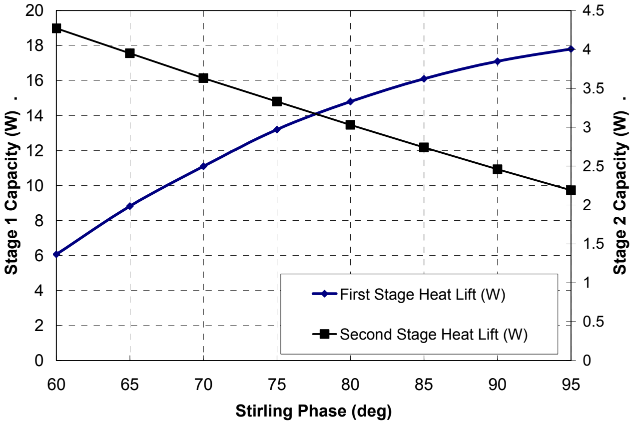

FIGURE 6. HC-RSP2 Load Shifting Curves. Cryocooler input power ~ 475 W for all points shown. Reducing phase angle shifts capacity to the second stage, and vice versa. T_1 = 85 K. T_2 = 35 K.

One of the attractive features of the Stirling/pulse tube architecture is the compatibility with existing flight electronics architecture from our single stage Stirling line because the number and basic operating characteristics of the motors is the same. However, development efforts are underway to develop a next generation cryocooler electronics module with reduced parts count, higher efficiency, higher reliability, and increased radiation hardness. The new electronics module will provide simultaneous two-stage temperature control, basically utilizing the same unique partial coupling mechanism that enables the load shift behavior shown in FIGURE 6. A major improvement will be the incorporation of an active line filter to attenuate current ripple onto the spacecraft bus by over 30 dB. Details on the next generation electronics will be presented in a future paper.

In summary, two versions of the RSP2 Cryocooler are planned to achieve flight readiness by the end of 2007. The RSP2 is compatible with present Raytheon space cryocooler electronics, making it immediately deployable on a space system. Next generation electronics which will provide better efficiency and advanced temperature control are in development.

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