Coaxial Pulse Tube Microcryocooler

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ABSTRACT

We report the successful completion and initial testing of the Lockheed Martin first-article, single-stage, compact, coaxial pulse tube microcryocooler. This cryocooler supports cooling requirements for emerging high operating temperature (125-150K) infrared focal plane array sensors with nominal cooling loads of ~500mW@125K. We present new coaxial pulse tube cooling performance test measurements with comparisons to the design predictions and the in-line pulse tube measurements. The microcryocooler exhibits small size, volume, weight, power and cost features that warrant further component enhancements and manufacturing process maturation for a variety of space and tactical applications.

INTRODUCTION

A low SWaP (size, weight, and power) prototype single-stage, coaxial pulse tube microcryocooler (PTM) was successfully completed, tested, and integrated by Lockheed Martin into a new High Operating Temperature (HOT) nBn mid-wave infrared (MWIR) camera system. This effort follows the development of the initial high-performance microcompressor component reported at the 2013 Cryogenic Engineering Conference in Anchorage, AK[1]. The new first-article PTM includes an optimized compact cold head and dewar assembly developed and tested in 2013. The referenced paper provides the motivation and plan for development of this scale microcryocooler device that is intended for both tactical and space cooling applications[1]. This paper provides updated specifications, initial performance measurements, and modeling results on the completed coaxial PTM. Additional in-line measurements are also presented for better understanding and developing near-term coaxial PTM enhancements.

COAXIAL PULSE TUBE MICROCRYOCOOLER

Figure 1 shows the split configuration PTM — comprised of the microcompressor, cold head assembly, and transfer tube. The cold head shown at the top consists (from right to left) of the cold tip, pulse tube, warm flange, and reservoir volume that contains the inertance tube.

The dimensions of the first-article microcryocooler are shown in Figure 2. The micro- compressor size is 90mm x 32mm diameter and consists of two moving magnet motor modules with

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Figure 1. First Article Coaxial Pulse Tube Microcryocooler.

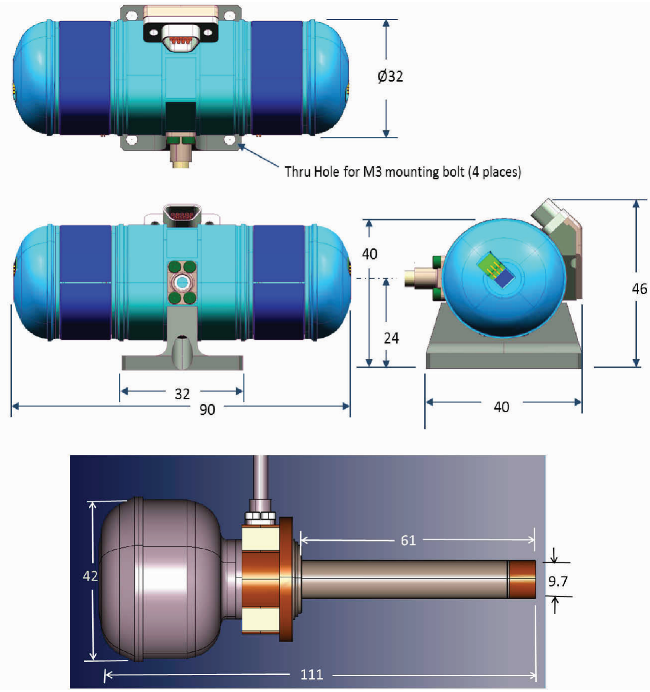

Figure 2. Microcompressor and Cold Head Assemblies (dimensions in mm).

dual-opposed pistons and a central hub. The pulse tube cold head assembly is 111 mm long and 42 mm diameter. The cold finger is 61 mm long with a 9.7 mm diameter.

The first-article microcryocooler weighs 328 grams. This includes the 118 grams cold head assembly and the 210 grams microcompressor. This does not include the mass of the dewar, sensor, or cooler drive electronics. The cold head mass can be reduced to 65 grams by replacing the copper warm flange with aluminum. This is one change being considered in a subsequent fabrication.

The Lockheed Martin microcompressor design includes long-life flexure bearings and several key fabrication methods and procedures that minimize assembly labor. These features translate to increased device reliability and lower projected costs for the tactical cooler applications (assuming a reasonable production volume).

Figure 3 shows the first-article PTM assembled with the dewar. The dewar houses the camera window, an IR cold filter, a cold shield to limit stray radiation, the IR focal plane array (FPA), a getter, and the readout integrated circuit (ROIC) cold-side electronics required for camera functional interfacing. The FPA is attached to the end of the cold finger and is surrounded by a cold shield inside the evacuated dewar.

Figure 4 shows the integrated dewar detector microcryocooler assembly (IDDMA) installed into the camera chassis. The overall size of the prototype camera (excluding the IR lens) is: 7.2" x 4.6" x 3.9" (18.3 x 11.7 x 9.9 cm). It has not yet been optimized for size in order to minimize risk and focus on the PTM development. The cooler and camera electronics used were developed for another system. Even with these non-optimized subsystems, the layout shown is smaller than typical high performance IR cameras. There are several paths that can be pursued to repackage the subsystems in order to modify or minimize size, weight, and/or volume of the prototype.

COAXIAL PULSE TUBE MICROCRYOCOOLER PERFORMANCE

Coaxial Pulse Tube Microcooler Cooling Load Lines and Cool Down Time

The measured first-article coaxial PTM load lines are shown in Figure 5. The left graph shows the net cooling power as a function of cold tip temperature (K) for compressor electrical input powers spanning 5 to 20W at a heat rejection temperature of 300K. The graph to the right shows the specific power (electrical power / cooling power) also as a function of the cold tip temperature and compressor electrical input power. The design was optimized for the temperature range of 125-150K specifically for use with Hot IR nBn FPAs but provides cooling capability at other temperatures as

Figure 3. Integrated Dewar Detector Microcryocooler Assembly (IDDMA).

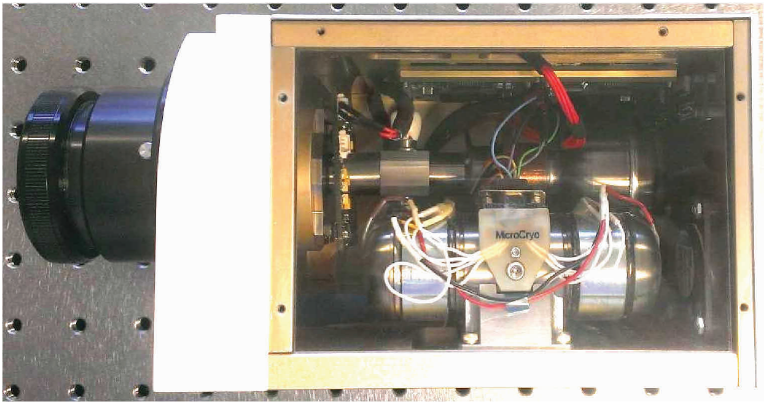

Figure 4. HOT nBn MWIR camera with installed microcryocooler.

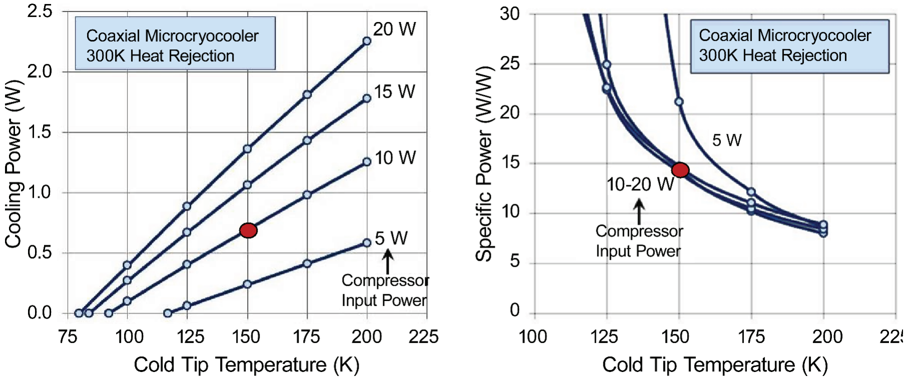

Figure 5. Coaxial Pulse Tube Microcryocooler Cooling Power and Specific Power Measurements.

well. The highlighted 150K design point shows a net cooling power of 690 mW with a specific power of 14.5 W/W. The PTM can also provide 400 mW of cooling power and 25 W/W specific power at a cold tip temperature of 125K. These values meet initial microcryocooler project goals and meet the cooling needs for HOT IR FPAs.

The measured load lines show that the first-article PTM is capable of higher input power and cooling. This provides adequate margin for many cooling applications. The PTM can operate with a heat rejection temperature as high as 71°C and as low as cryogenic temperatures[2]. The ability to operate over a wide range of ambient temperatures typical of ground tactical requirements and military specifications is an important feature of the PTM. Excess cooling capacity is not exhibited in most other "low SWaP" camera systems emerging commercially. Their cooling capacity, specifically at the higher ambient temperatures, may prove to be insufficient for ruggedized tactical needs.

Table 1 presents a performance summary of the first-article compact coaxial pulse tube microcryocooler. This table lists key cooler parameter measurements at the two temperature design points and weights of the two cooler subassemblies.

The microcryocooler was also subjected to thermal and vibration environmental testing required for space-qualified use. The unit admirably passed these tests qualifying it at a Technology Readiness Level (TRL) of 6, an important step toward space readiness. These test results and associated space applications are reported in a companion paper at this conference[2].

Table 1. First Article Coaxial Pulse Tube Microcryocooler Performance.

FIRST-ARTICLE 2013 MICROCRYOCOOLER PERFORMANCE SUMMARY

Parameter	Value		Comments
Cold Tip Temperature	125K	150K	
Ambient (Reject) Temperature	300K	300K	
Net Cooling Power	400mW	690mW	10 W Input
Specific Power	25.0 W/W	14.5 W/W	
Cooldown Time	11 min	8 min	20 W Input
Electrical Drive Power (Maximum)	25 W		
Operating Frequency	100 Hz		
Total Microcryocooler Mass	328 g		without dewar
Microcompressor Mass	210 g		
Cold Head Assembly Mass	118 g		
Ambient Operating Temperature	+71°C to -150°C		
Operating Life (MTBF) (calculated)	Reliability=0.98 @ 10 years		
Low Exported Vibration			

The initial cool down time measurements are plotted in Figure 6 and listed in Table 1. The microcryocooler was not optimized to minimize cool down time, but reducing cool down time for the tactical ground applications is part of ongoing 2014 performance enhancements, with a goal of 2-3 minutes between turning on the cooler and the onset of IR imaging.

Coaxial and In-Line Pulse Tube Microcooler Performance Comparison

Figure 7 compares the measured cooling power for the coaxial pulse tube with the previous in-line pulse tube microcooler measurements presented in 2013[1]. The measurements show that the coaxial cold head performs slightly better than the in-line cold head despite having a hotter ambient environment. The in-line cold head is still an important optimization tool, since it is easier to test the effects of design changes using the in-line test cooler prior to committing to the fabrication of a coaxial cold head.

In-Line Pulse Tube Microcooler Orientation Dependence

Pulse tube coolers usually have some sensitivity to orientation with respect to gravity. Performance is best when the pulse tube is oriented with its cold end down; degraded performance is usually observed as the tube is tilted away from vertical. Figure 8 shows measured data from the in-line pulse tube cooler as a function of the tube's orientation (0° is the cold end down). For a ground-

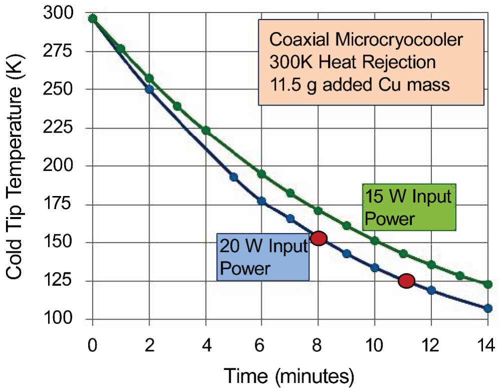

Figure 6. Coaxial Pulse Tube Microcryocooler Cool Down Time Measurements.

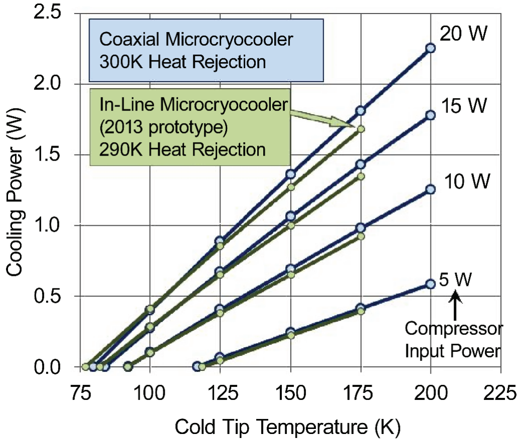

Figure 7. Comparison of Coaxial (blue) and In-Line (green) Pulse Tube Microcryocooler Measurements.

based camera, the pulse tube is usually oriented horizontal (90°). This horizontal position is annotated on the measured data shown in Figure 8. The data show that, at a constant electrical input power of 20W, 8% of the cooling power is lost when tilting from vertical to horizontal. Thus, this effect is significant. Modifying the cold head orientation within the camera package may be desired to minimize input power.

Comparison of Measured and Predicted Cooling Power

Figure 9 compares the measured coaxial PTM load line shown in Figure 5 to the predicted PTM model results. As observed, the agreement is very good, with differences only on the order of 10%, and with a closer agreement in the temperature range and power level of primary interest. Modeling confidence grows as more measurements reasonably correspond to model predictions. Consequently, modeling is being used to assess a variety of design changes to our baseline microcryocooler configuration.

Coaxial Pulse Tube Microcryocooler Enhancements

Threshold cooling power goals were met for the first-article coaxial PTM. Desirable objective goals include lower specific powers obtained by higher efficiencies (e.g., ~10-12 W/W @150K). An Enhanced Pulse Tube Microcryocooler study task began in 2014 using in-line pulse tube measurements (with the current microcompressor) to perform trade-offs of promising engineering improvement approaches. Lockheed Martin pulse tube model predictions were also used to guide and assess results.

Topics of the 2014 experimental and modeling studies for an enhanced PTM include:

- Warm flange mass redesign with lighter materials and reduced size
- Cool down time reduction (required for tactical ground applications)
  - Higher electrical drive / higher cooling power
  - Lower heat capacity / lower thermal mass dewar
  - Pulse-tube redesign (reduced length, diameter, and wall thickness)
- Reservoir Volume Reduction
- Cold head / Inertance Tube Repackaging
- Regenerator / Heat Exchanger Improvements
- Motor modifications
- Improved Cooler Electrical Drive Control

The experimental in-line pulse tube measurements, modeling predictions, and analyses of initial results were promising. The improvements are being prioritized. Some will be implemented

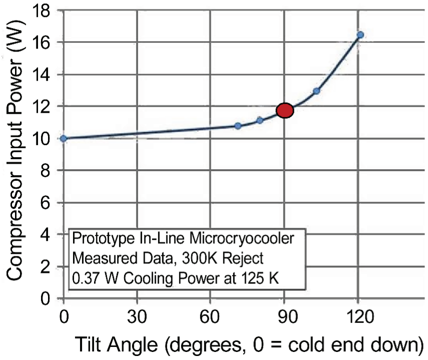

Figure 8. In-Line Pulse Tube Microcryocooler Orientation Measurements.

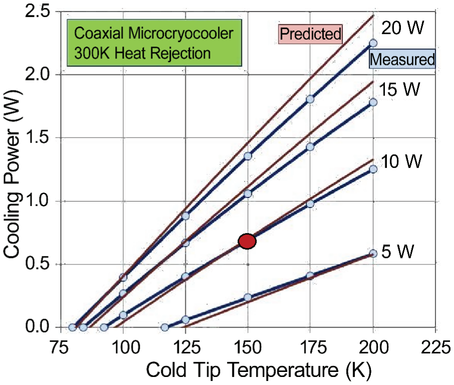

Figure 9. Comparison of Measured (blue) and Model Predicted (brown) Coaxial Pulse Tube Cooling Power.

and tested in the next "enhanced coaxial pulse tube" cold head and dewar development expected to be completed in 2014. Selected demonstrated results will be presented in 2015.

SUMMARY

This paper presents continuing progress of our microcryocooler project. We report completion and testing of the first article compact coaxial pulse tube microcryocooler as a sequel to the previous completion of the microcompressor and in-line tests presented in 2013[1]. This new unit demonstrates adequate cooling power performance, especially for a first article unit. Additional effort is in progress to enhance performance in several critical areas. An area of interest for AMRDEC tactical applications is reducing the closed-cycle cool down time in order to meet rapid deployment needs while retaining benefits of the now-demonstrated or projected size, weight, power, and cost improvements of a coaxial microcryocooler.

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