Development of Remote Cooling Systems for Low-Temperature, Space-Borne Systems

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ABSTRACT

Lockheed Martin's Advanced Technology Center (LMATC) has developed advanced cryocooler technology to provide temperatures of 10 K and below for cooling space and terrestrial payloads. For some payloads, cooling is required remote from the cryocooler.

Over the past few years we have developed numerous staged coolers, which provide temperatures as low as 3.8 K, and are extending this technology to provide remote cooling while maintaining our simple, high-reliability approach.[1,2] Our approach employs our multiple-stage pulse tube in combination with an integral flow loop. This flow loop circulates a small fraction of the working fluid from the cryocooler compressor. As a result, only a single compressor is required. The flow loop utilizes constant (DC) flow to provide cooling at temperatures near 6 K at the remote cooling location. No Joule Thomson (J-T) expansion is utilized in this approach, greatly simplifying the hardware and reducing the number of components. This approach increases reliability and reduces weight compared with the J-T approach.

Our four-stage pulse tube cryocooler was developed under the very successful Advanced Cryocooler Technology Development Program (ACTDP) under contract to the Jet Propulsion Laboratory (JPL).[3] The development of the remote cooling loop was jointly supported by JPL and LM research funding. Extensive performance data for the four-stage ACTDP pulse tube cooler are described. In addition, preliminary data and performance of the pulse tube system, integrated with a 20-meter long flow loop, are also presented.

INTRODUCTION

Lockheed Martin's Advanced Technology Center (LMATC) has been actively developing multiple-stage pulse tube technology for long-life space operation since 1996 and demonstrated a three-stage pulse tube system in 2001 under LM funding.[1] That first system achieved 6 K and was the first demonstration of cooling in this temperature range while utilizing a long-life linear drive compressor without augmentation by a J-T stage. Although pulse tube systems had previously attained temperatures in this range, they operated at a few Hertz frequency and are not compatible with long-life linear compressors. It was obvious from the start that pulse tube coolers, which have no moving parts, could be staged without difficulty as long as the thermodynamic design was understood and could be implemented.

Cryocoolers 14, edited by S.D. Miller and R.G. Ross, Jr.

Table 1. Summary of low temperature (< 10 K) pulse tube cryocoolers developed by LMATC.

Program	Stages	Requirement	Test Data	Comments
LMATC funding, 2000-2002	3	8 K (Goal)	No load of 6 K, P = 120 W 0.125 W at 10 K, P = 240 W	Three-stage technology demonstration
ACTDP, 2003-2006	4	0.02 W @ 6 K and 0.15 W @ 18 K	Cooling achieved with 208 W	No load temperature of 3.8 K achieved
AFRL, 2004-2005	3	0.2 W @ 10 K and 8 W @ 75 K	0.2 W @ 10 K and 8 W @ 83 K with 450 W	
HYPRES/ARMY, 2005-2006	4	0.1 W @ 4.5 K	Tests scheduled for October, 2006	In fabrication

LMATC has built two three-stage coolers and one four-stage cooler with excellent results. A summary of the cryocooler systems developed by LMATC producing temperatures below 10 K is shown in Table 1—stated power is that input to the compressor. These coolers demonstrate excellent agreement between thermodynamic modeling and measured performance. We are currently developing a four-stage unit for superconducting electronics requiring 4.5 K cooling. This experience base has confirmed our ability to routinely produce pulse tube cooling systems in the 4 to 10 K range. Since the pulse tube cold head has no moving parts and has extremely high reliability, the compressor and electronics set the reliability; this is the same as the many single stage systems that have been developed and proven in a wide range of applications, both in space and on the ground.

Although these low temperatures are now being achieved in a routine manner at LMATC, some advanced missions require the cryocooler to provide cooling at a remote location.[3] This is achieved by some form of flow loop. The reasons for this include: 1) isolation of the warm compressor/pulse tube with its heat dissipation from passively cooled very low temperature sensor systems, 2) removal of the principle vibration source, the compressor, from the vicinity of the sensitive detectors, and 3) packaging or space restraints.

Recently the cooling system for the JPL Mid-Infrared Instrument (MIRI), one of the James Webb Space Telescope (JWST) instruments, was redirected to utilize a mechanical cryocooler. The cooling was previously provided by a solid hydrogen cryostat, being developed by LMATC, which was discontinued in a weight saving effort. Our recent work at LMATC on the pulse tube system has been focused on providing the remote cooling required by the MIRI instrument 10 meters from the cryocooler. The LMATC-developed concept achieves this without adding significant components to the cryocooler. This is made possible by our attainment of the required temperatures (6 K) with the pulse tube alone. This relatively simple approach increases reliability and reduces weight.

COOLER DEVELOPMENT AND PERFORMANCE

Cooler Design and Configuration

A schematic of the cryocooler system and its component weights without the remote flow loop is shown in Figure 1. This system utilizes one of our standard series of linear drive moving magnet compressors, employing clearance seals and flexure supports; these result in a nonwearing long-life system. The design of the compressor eliminates nearly all of the organics in the system, greatly reducing the condensable gases that can freeze in the cold areas. Before, when we utilized moving coils, LMATC Stirling systems had over 90% of the condensable gases coming from the potted coils. Another advantage of our moving magnet compressors is that they have no electrical penetrations into the working gas space, and flexing current leads have been eliminated. The piston size is optimized (increased) to meet the required cooling loads with minimum power. The compressor is shown in Figure 1 attached to a heat rejection plate for both heat rejection and structural support.

The connecting tubing between the cold head and compressor includes the gas transfer line and the inertance tube. Also shown is a loop heat pipe utilized to remove the heat from the cold head. The majority of the system heat (75%) is removed at the cold head mounting flange.

The electronic controller design is shown to the left in Figure 1. The controller includes active ripple suppression, precision temperature control, and vibration control loops. The systems are typically radiation tolerant to 100 krad, or higher, with high reliability (0.96 for 10 years).

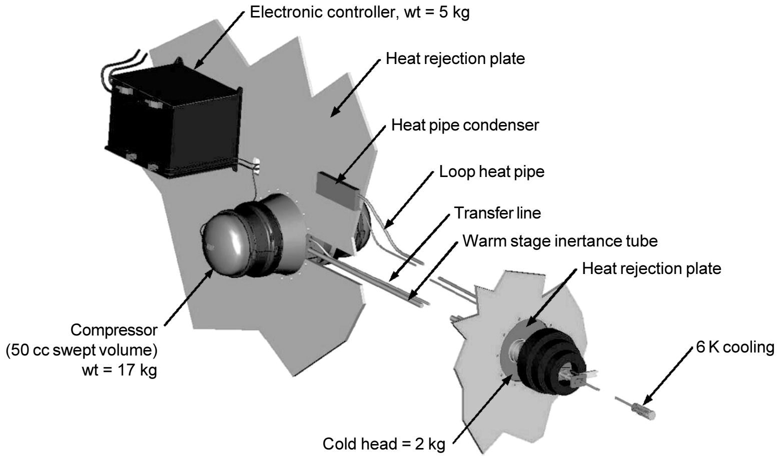

Figure 1. LM four-stage pulse tube system without flow loop.

The system weight is 25 kg, not including cables and some of the mounting hardware that may increase the system weight to approximately 28 kg.

Performance of ACTDP Cooler

We first describe the cryocooler performance without the flow loop. We tested two configurations of the cooler; the first was designed to meet the ACTDP requirements (0.02 W at 6 K and 0.150 W at 18 K), while the second version (designated ACTDP/MIRI) was modified to maximize the cooling at 6 K for the MIRI instrument requirements with our flow loop arrangement.

Our four-stage cooler achieved the specified cooling loads of 0.02 W at 6 K simultaneous with 0.15 W at 18 K with 208 W of compressor input power. These results were attained after extensive test optimizations which varied the operating frequency and charge pressure. The data in Figure 2 show the cooling capability at 6 K and 18 K at various charge pressures with 240 W of compressor power input. The impedances were unchanged during this series of tests. At this power input, the specified ACTDP cooling loads of 20 mW at 6 K and 150 mW at 18 K are substantially exceeded.

Figure 3 shows the interaction of power and operating pressure to achieve the specified 20 mW at 6 K and 150 mW at 18 K. This is achieved with ^{3}He working gas. We predicted that the utilization of the rare isotope ^{3}He would improve performance and verified this with test data. The minimum

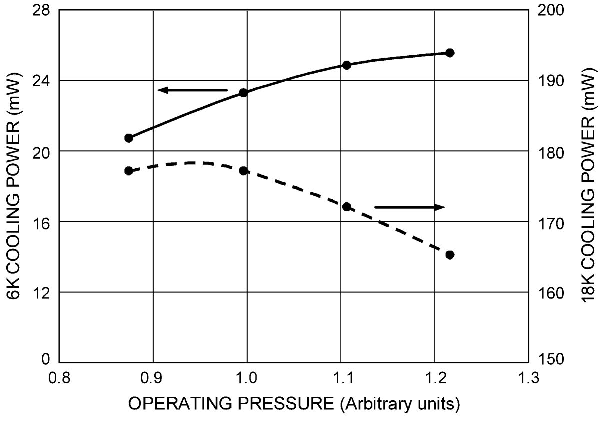

Figure 2. Effect of operating pressure on cooling loads at 6 K and 18 K, with 240 W compressor power and ^{3}He working gas.

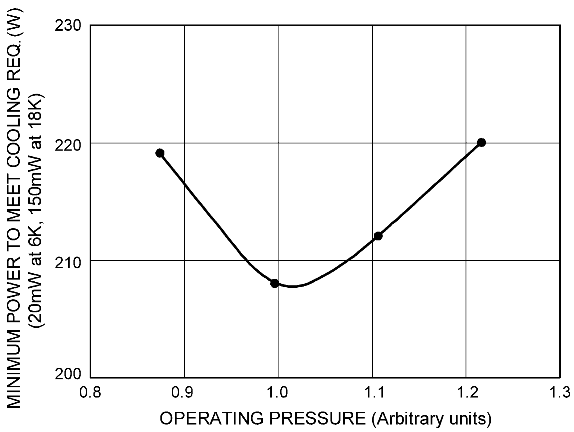

Figure 3. Locus of input power and operating pressure to achieve required cooling loads.

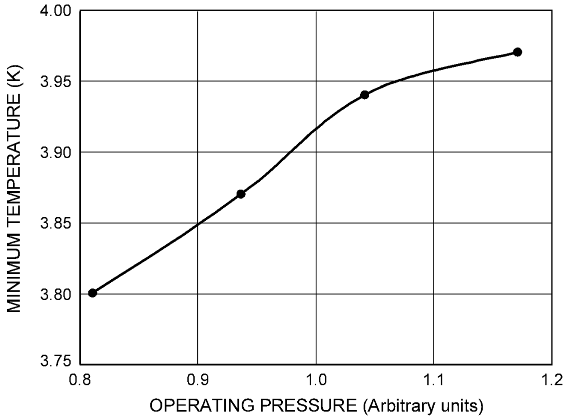

Figure 4. Effect of operating pressure on no-load temperature.

power to meet the requirements is 208 W into the compressor. Figure 4 shows the effect of operating pressure on the no-load temperature. At pressures below 0.8 units, the compressor stroke approaches its limit for 240 W power input. The 3.8 K no-load temperature is the lowest temperature yet achieved with a pulse tube cryocooler operating at the relatively high frequency normally required (30-60 Hz) with a linear compressor.

An additional set of tests was conducted to determine the effect of orientation of the cold head with respect to gravity. Since the pulse tube is empty with a temperature difference from one end to the other, free convection of gas can transfer heat along the length and decrease the cooling. The pulse tube operates best in a 1-G gravity environment with the cold end down. In this orientation the gas is stable and mimics the performance in space where free convection effects are absent. A tilt stand was fabricated, and the system was tested at tilt angles up to 90 degrees. These data were obtained with ^{4}He. Additional data at higher angles and with ^{3}He were not obtained due to test priorities. These tests were run with no heat input to the 1st, 2nd and 4th stages, but heat input was added to the third stage to maintain 18 K up to angles of 67 degrees. At angles above 67 degrees there was no heat input to any stage. These test data show that the temperatures of all four stages remain nearly constant up to 67 degrees. Somewhere between 67 and 90 degrees there is a significant increase in all temperatures. Prior test data on other systems at LM show that the level of degradation is strongly dependent upon the length-to-diameter ratio of the pulse tube, as would be expected for free convection. Additional operating conditions affecting the degradation versus tilt

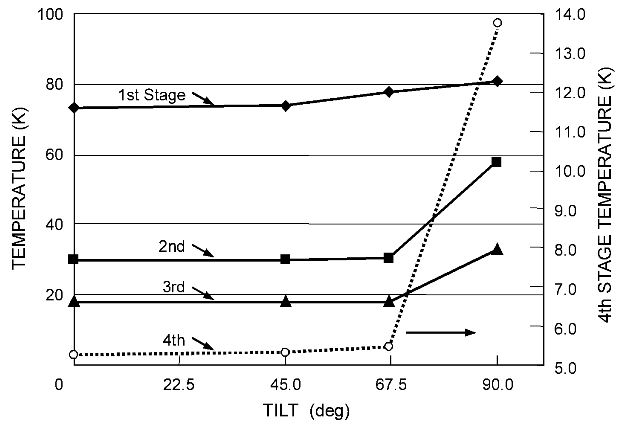

Figure 5. Effect of cold head tilt angle on stage temperatures (0 degrees is cold head down), working gas is ^{4}He.

were found to be operating frequency and charge pressure. These factors were investigated at a preliminary level.

Performance of ACTDP/MIRI Cryocooler

For the MIRI instrument, our proposed approach utilized a DC flow loop operating at 6 K to directly provide cooling gas to the instrument. For other suppliers using hybrid J-T systems the flow loop gas temperature is transferred near 18 K and then expands in a J-T orifice to the MIRI required temperature of 6 K.

In order to implement our simple approach, it was desirable to eliminate the cooling at 18 K on our cryocooler and maximize the cooling near 6 K. Our four-stage ACTDP cold head was modified by changing the inertance tube impedance to achieve this. The success of this approach demonstrates the capability to easily modify an existing cold head to redistribute the cooling temperatures and loads.

Tests were conducted with both ^{3}He and ^{4}He, clearly demonstrating the superiority of ^{3}He at these temperatures. Figure 6 compares the load lines using ^{3}He and using ^{4}He at the optimum charge pressure and frequency with a compressor power input of 300 W. At 6 K the ^{3}He provides 50 mW of cooling compared with 27 mW with ^{4}He, nearly double the cooling at the same power. Prior to the impedance modifications the maximum cooling at 6 K (no cooling at other stages) with ^{3}He, was

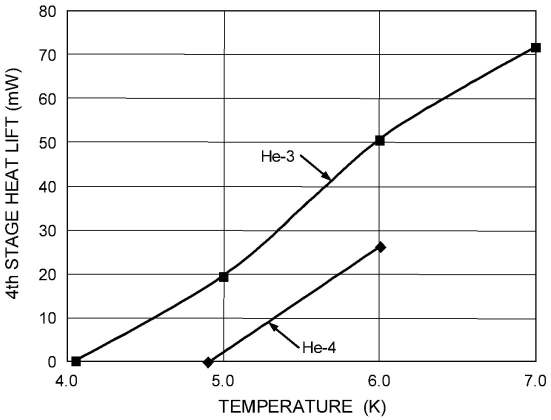

Figure 6. Cooling at the 4th stage only with ^{3}He and ^{4}He for ACTDP/MIRI version, power = 300 W.

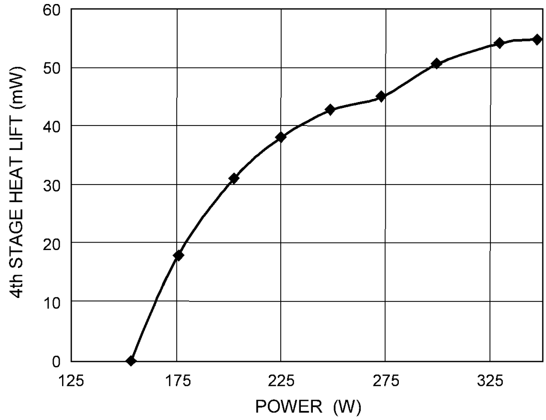

Figure 7. The effect of compressor input power on cooling at 6 K with ^{3}He.

32 mW with 300 W of power. This increase from 32 mW to 50 mW due to impedance changes illustrates the capability to modify the cooling distribution. Varying the drive frequency and charge pressure also provides additional means to alter the distribution of cooling among the stages. Figure 7 shows the cooling achieved at 6 K for various compressor input powers.

Tests of ACTDP/MIRI Cryocooler Integrated with the Flow Loop

In order to achieve the remote cooling for the MIRI system, a flow loop concept was developed and tested at LM. This flow loop operates by withdrawing a small quantity of He from the compressor. This gas is rectified by a reed valve which converts the periodic (AC) flow stream to a continuous DC flow stream. This DC flow passes through counter-flow recuperators and exchanges heat with the four stages of the cold head to cool to below 6 K. It then continues 10 meters to the MIRI instrument where it removes heat at the instrument heat exchangers and then flows back to the compressor through the recuperator. Effectively, the main compressor used for the cryocooler also acts as a circulator. LM considered this approach to be very attractive since it eliminates many of the complexities of the hybrid J-T system, and is possible only because we can achieve the required temperatures directly with our four-stage pulse tube. A schematic of this system is shown in Figure 8.

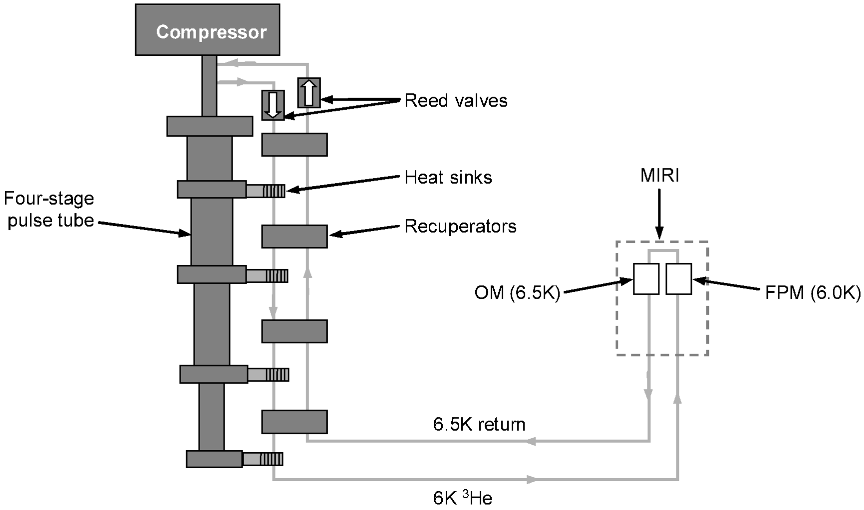

Figure 8. Flow schematic of the cryocooler integrated with the flow loop.

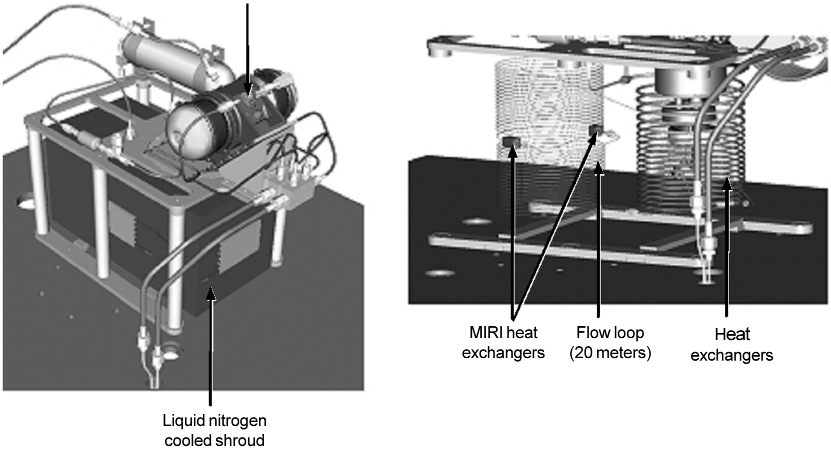

Figure 9. Cryocooler integrated with flow loop.

This system has several advantages over the hybrid cryocooler/J-T system. The reduced number of components leads to a substantially higher reliability and lower weight and leads to simpler integration with the instrument. The cooldown time of this approach is shorter than the hybrid system and does not require valves to bypass the J-T flow during early phases of cool down.

One of the features of the system that requires additional development is the parasitic heat load into the transfer line (20 meters for MIRI). For the MIRI application, the radiating source temperatures vary from 40 to 80 K. Because the flow loop gas is transferred at 6 K, any heat loads on the line must ultimately be rejected at 6 K in the cold head. This feature places a premium on reduction and accurate prediction of these parasitic heat loads. Although the predicted radiation heat loads for a clean low emittance line are extremely low (emittance values of 0.01 should be achieved) and lead to values of 2 mW, (a negligible value compared to the MIRI instrument loads of 65 mW), the possibility of cryopumping water vapor onto the surface is a common problem and could have a dramatic effect on heat rates. Emittance values of 0.1 to 0.2 or higher are possible for contaminated surfaces.[4] There are several approaches to deal with this, such as wrapping MLI around the tubing and/or a cold shield/trap around the tube which would cryopump and retain the water vapor and prevent it from reaching the low emittance tubing surface. While these systems should effectively eliminate this problem, demonstrations are required to validate and quantify these approaches.

We have integrated a flow loop with our cryocooler and initial tests are promising. Figure 9 shows this system. Some major elements of the system include a 20-meter flow loop with MIRI simulated heat exchangers, and a liquid-nitrogen cooled shroud to simulate the thermal conditions of the MIRI system. Although we intended to run the system with ^{3}He, the initial checkout runs were with ^{4}He. Additional testing with ^{3}He is planned for the future. The results from the first test were quite encouraging. The reed valve provided the predicted flow (measured with a flow meter)—the cold tip ran at 12 K, and the MIRI instrument location ran at 12.7 K. The target temperature of 6 K was not achieved in this test, since the ^{4}He working gas has only about half of the cooling capacity of ^{3}He. Inspection of the system after the first test series indicated that we had a thermal short in a region of the flow line, which also increased the cold tip temperature. Additional tests are planned with ^{3}He and with elimination of the thermal short.

CONCLUSIONS

The development of the pulse tube cryocoolers met the required cooling of the ACTDP program. Tests comparing the use of ^{3}He and ^{4}He conclusively demonstrated the superiority of the ^{3}He as predicted by thermodynamic modeling.

A redirection in the MIRI cooling system from solid hydrogen to a cryocooler, led us to modifications of the cold head and the incorporation of a simple, efficient flow loop to help meet MIRI requirements.

This flow loop was integrated with our cryocoolers and initial testing was very promising. Future tests with ^{3}He, improved thermal isolation of the flow loop, and improved heat exchangers are planned.

ACKNOWLEDGMENTS

We wish to acknowledge the support and sponsorship of this project by the Jet Propulsion Laboratory California Institute of Technology. Additionally, Lockheed Martin provided internal funding to support this work.

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