10 K Airborne Cryocooler and High Efficiency Heat Exchangers

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ABSTRACT

Ball Aerospace has designed, built, and characterized a compact refrigeration system for cooling very low temperature infrared imagers. The system is robust, will be integrated into an airborne application, and can also be used in space environments. This paper reviews the completed system testing and results as well as component testing of the high efficiency, micro-channel heat exchangers, which are an enabling technology for this cooler system. The system is a hybrid of complementary Stirling and Joule-Thomson (J-T) cycle cryocoolers. The Stirling is a version of our standard two-stage SB235E cryocooler with its second stage optimized for cooling below 20 K. The J-T cycle, which provides the refrigeration at 10 K, uses a reed valve equipped Oxford style compressor to drive a compact cold head which is precooled by the Stirling cooler. The cold head consists of three counter flow heat exchangers, a bypass valve, and an expansion valve packaged on a small diameter, mechanically robust cryostat.

INTRODUCTION

In 2002, Ball Aerospace built a hybrid cryocooler to meet the distributed low temperature cooling requirements of the NASA sponsored Advanced Cryocooler Technology Development Program (ACTDP) [1]. The purpose of the ACTDP program was to develop a refrigerator for cooling the MIRI instrument on the James Webb Space Telescope to 6 K. Since that time, several variations on that basic cooling concept have been explored at Ball on internal and external programs. The purpose of this paper is to provide test results for a mature, compact version optimized for use at 10 K.

A hybrid cryocooler uses two coolers to carry out a task that is difficult to achieve with either cooler by itself. Our 10 K cooler uses a Stirling precooler to cool the system from room temperature to about 17 K and a J-T expansion cooler to efficiently cool the system down to 10 K. A schematic of our hybrid configuration is given in Figure 1.

Cooling to 10 K with the Stirling alone is difficult because of the rapid falloff in its efficiency below 20 K. The Stirling relies on a regenerator material to store heat during its cycle, but common regenerator materials lose their heat capacity at low temperatures. Using the J-T, which readily cools to 10 K, saves power and enables cooling circulation to a remote load.

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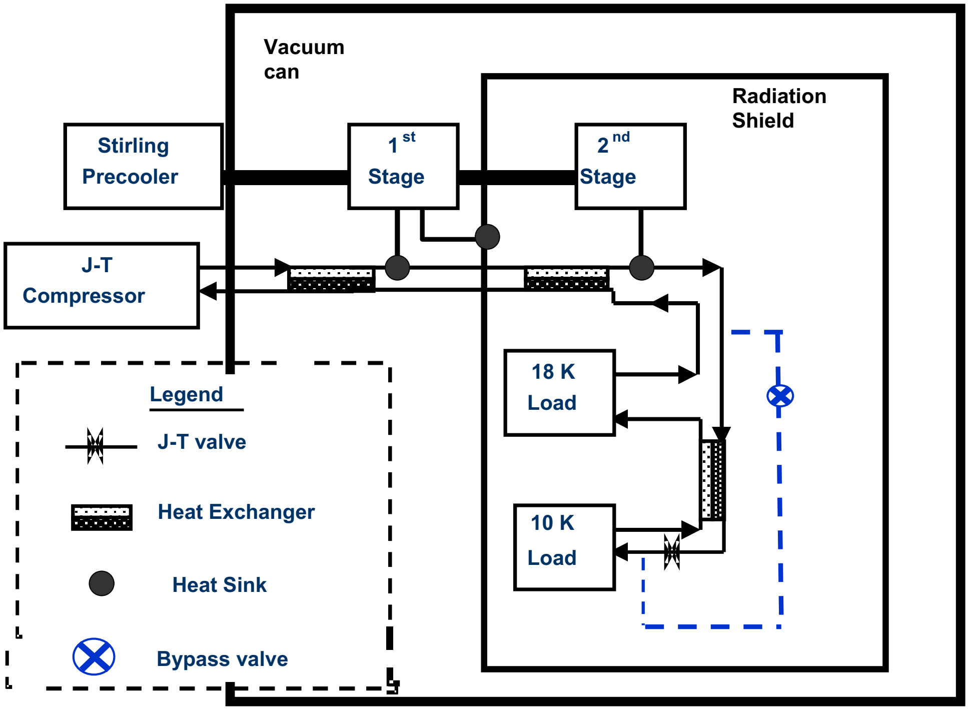


Figure 1. A schematic of our hybrid cryocooler showing the precooler and key elements of the J-T flow loop.

The schematic in Figure 1 shows how the J-T circulates a cold fluid to the remote 10 K load. The J-T does not need a regenerator because the fluids exchange heat with each other in the recuperative heat exchangers. The flow loop shown in Figure 1 includes three recuperative heat exchangers, heat sinks at the precooler and at two customer interfaces, and the J-T valve. Expansion cooling at the valve, where the main pressure drop takes place, refrigerates the helium gas used to cool the load.

BALL'S 10 K CRYOCOOLER

The Ball 10 K cooler is an evolution of the technology developed on the ACTDP program. Each major component was rebuilt to make it more robust. The components were then integrated together into a compact module. The module is to be a basic refrigeration bus for both airborne and space infrared applications. Its main attributes will be discussed in this section.

Stirling Precooler

The precooler is a special version of our standard 35 K two stage cryocooler, the SB235E. The "E" is an Oxford style flexure bearing, clearance seal cooler operating at approximately 40 Hz. The mid stage of the 10 K version intercepts 3-5 W at approximately 70 K for cooling an intermediate radiation shield. It's cold stage, normally good for 2 W at 35 K, was modified to enhance its performance at lower temperatures. The second stage provided net cooling of over 100 mW in addition to supporting the J-T stage precooling and system heat load parasitics. The Stirling cooler's mass is approximately 17.5 kg.

J-T Compressor

The J-T compressor is Ball's SA160; a flexure bearing, clearance seal compressor previously used to power a Stirling cooler. For this application it was equipped with reed valves to generate the DC flow. The reed valves are based on those used by RAL for the Planck instrument. The compressor operates at a modest pressure ratio since it only provides the cooling from the precooler cold tip temperature to 10 K. The J-T compressor's mass is approximately 8 kg.

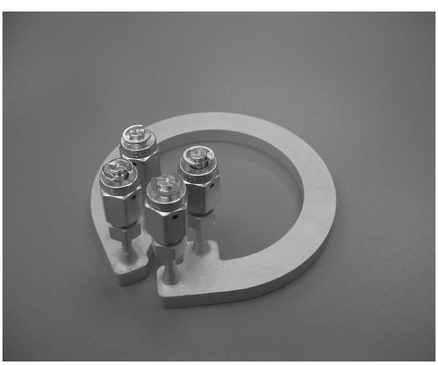
Microplate Recuperative Heat Exchangers

Our hybrid cooler uses three counterflow heat exchangers, one from ambient to the mid-stage, the second from the mid-stage to the cold tip, and the third from the cold tip to the J-T valve. In the original ACTDP 6 K hybrid cryocooler cryostat, these exchangers were "tubes-in-tube" types that were each between 3 and 5 m long. In that application they were coiled into a helix with a diameter of 25 cm and a height of 40 cm. Although they had excellent effectiveness, their dimensions drove the size of the cryostat and limited performance at the larger mass flow rates required for this program. One of our goals was to reduce the size of the exchangers without compromising their effectiveness, enabling a compact system that would have fewer parasitics and be more robust in the field.

An extensive development program led to an equally effective set of heat exchangers that were 10 cm in diameter and less than 10 mm high. The compactness was achieved by photo-etching and diffusion bonding them in a stack. Care was taken to mitigate the flow misdistribution which in the past has prevented these heat exchangers from achieving the high levels of theoretical performance they can reach on paper. One of the new microplate exchangers is shown in Figure 2.

The heat exchangers were characterized in individual performance tests where the heat exchanger effectiveness was directly measured without the complications of other system components. Each exchanger was measured over a range of mass flow rates with fixed inlet temperatures and a calibrated heat flow sensor to measure the actual heat loss of the exchanger. All parasitic radiation and conduction losses in addition to the heat transfer losses are included in the measured heat loss. From this test the heat exchanger performance model is correlated using only a single parameter to fit the data. Next the correlated model is used to predict heat exchanger performance under the operating conditions in the overall system as shown in Figure 3. The individual heat exchanger predictions were used in the system performance model.

System level testing does not allow an accurate assessment of the heat exchanger performance. From system model correlation, we have good agreement with the #1 and #3 heat exchangers. It appears that the #2 exchanger is not performing as well as predicted. We have a number of real gas effects that could account for the difference in predicted performance. In future heat exchanger testing, we need to test under conditions more similar to operating



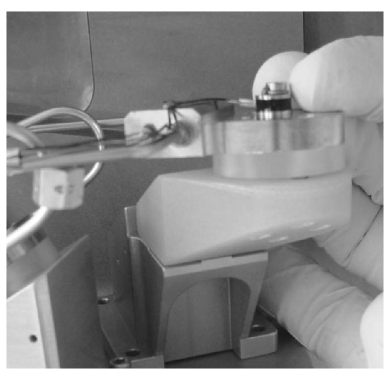


Figure 2. A microplate heat exchanger (left) and heat sink (right) used on the 10 K cryocooler.

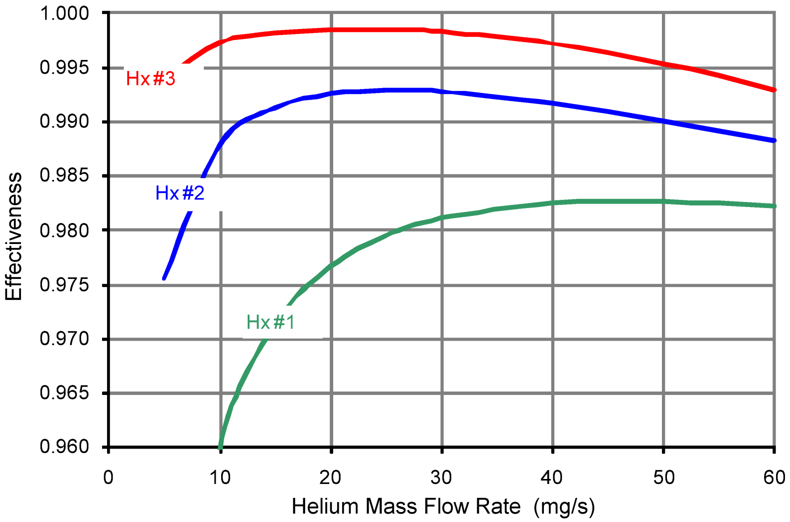


Figure 3. Heat exchanger performance at operating conditions.

conditions which will complicate the performance testing but will provide a better prediction for the system level modeling.

Heat Sinks

The system needs a compact heat sink to couple the cold fluid generated by the expansion at the valve to the customer's thermal interface. Ball developed the thermally conducting, electrically isolated heat sinks shown in Figure 2.

Bypass Valve and Cryostat

The bypass valve shown in Figure 1 is used to facilitate the cool down. The system's J-T valve is sized to have the correct flow characteristics at its operating temperature. However, at higher temperatures, it is too restrictive, and the remote load cannot be cooled by circulation alone. In ACTDP the remote load was cooled with an exchange gas. In this system, a solenoid valve that opens a path around the J-T valve and the last heat exchanger was added so the remote load could be cooled by circulation. The bypass stays open during the cool down until the load approaches the precooler's limiting temperature. At that time, the bypass is closed, and the J-T valve then provides enough refrigeration to cool the load the last few degrees.

Stiff, low conductivity struts support the various elements of our system within a small volume. The complete system is shown in Figure 4. The model shows how the Stirling cooler cold tip fits in the cold head, and how the 10 K heat sink is located off to one side.

CRYOCOOLER CONTROL ELECTRONICS

The entire system is driven by a custom set of electronics (Figure 5). They process the power, control sensors, provide communications via a serial port, and autonomously control both coolers. The CCE is an extension of the Stirling control electronics. The final package has a mass of 10 kg.

PERFORMANCE

A series of tests were performed to characterize the cooler's performance and repeatability. The cooler was operated over a period of several months. Each test included a cool down, a load

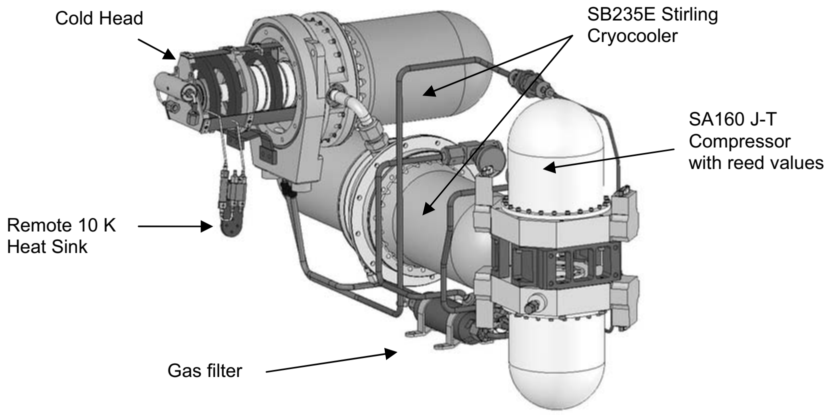


Figure 4. The 10 K Cryocooler has been packaged for use in an airborne system.

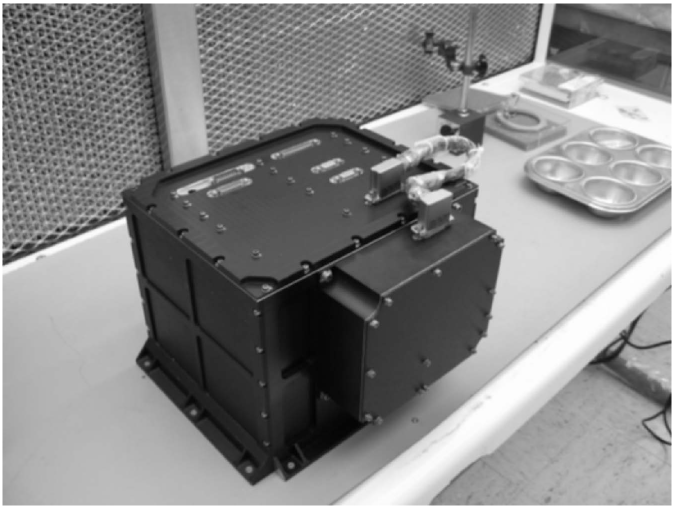


Figure 5. The Ball Cryocooler Control Electronics run the hybrid cooler autonomously.

line characterization, and operation at 10 K for a week or more. Over 500 hours of failure free run time was accumulated. No changes were made to the hardware or to the gas charge during this time. The aggregated normalized heat lift results are shown in Figure 6.

Figure 6 shows the repeatability of the 10 K performance. The cooler delivers this 10 K performance in addition to cooling at 70 K and at 18 K for other parts of the system. A typical cool down profile is shown in Figure 7. Most of the time is spent cooling the surrounding cryostat to below 20 K. The system cools rapidly once the bypass valve is closed, and the system enters J-T mode.

SUMMARY

A compact 10 K mechanical cryocooler has been developed and tested. The system is capable of 80 mW at 10 K. Good system repeatability has been demonstrated. Future tests will be performed to evaluate various aspects of system compatibility.

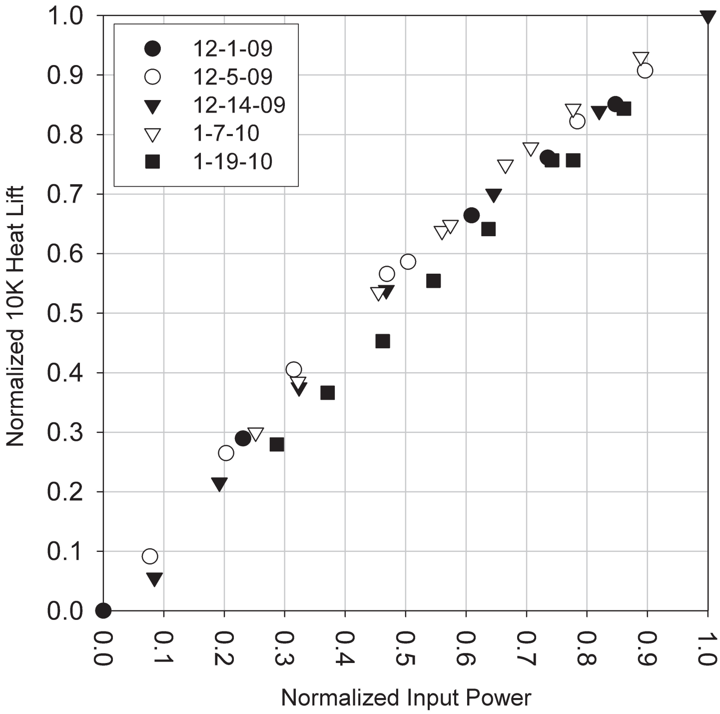


Figure 6. Normalized cryocooler heat lift at 10 K shows good reproducibility across five different runs starting on the dates given in the legend.

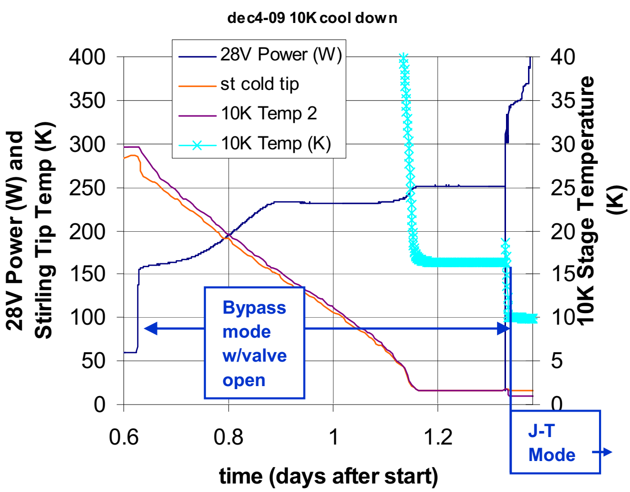


Figure 7. The system cools to 16 K overnight and, after entering J-T mode by closing the bypass valve, cools quickly to 10 K.

REFERENCES

1. Glaister, D., Gully, W., Hendershott, P., Marquardt, E., and Kotsubo, V., "Ball Aerospace 4-6 K Space Cryocooler," *Cryocoolers 14*, ICC Press, Boulder (2007), pp. 41-46.