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100 K Cooling Performance of a Modified Collins Cycle Cryocooler for In-space Applications

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Abstract. This paper presents 100 K cooling performance of a Modified Collins cycle cryocooler designed for in-space cooling applications. Descriptions of this lightweight, high efficiency, and power dense cryocooler design are included. Experimental results are shown of a single-stage floating piston design with active control designed to provide 100 W of cooling at temperatures below 100 K. Maintenance of in-space cryogenic fuels (liquid methane and liquid hydrogen) and liquid oxygen should be possible with this medium-scale, continuous flow architecture.

1. Introduction

Long duration space mission architectures that utilize cryogenic propellants require an on-board cryogenic cooler. Potentially, the cooler should be capable of providing tens to hundreds of Watts of refrigeration for methane (110 K), oxygen (90 K), and hydrogen (20 K) to achieve zero-boil-off and provide mission flexibility. In addition, the chosen cryocooler architecture should be capable of scaling to larger sizes for other applications such as liquefying propellants at a remote planetary base site.

Stirling and pulse-tube type architectures are compact and reliable but do not scale well to larger sizes. Conversely, turbo-Brayton, Collins, or Claude type machines achieve high thermodynamic efficiencies, but do not scale well to small sizes.

The modified Collins cycle cryocooler approach uses a Floating Piston Expander (FPE) that performs the gas expansion process without mechanical linkages. This expander concept, shown in Figure 1, was first proposed by Smith [1] in 2001. In the FPE, the stroke of the piston is controlled by the sequential opening and closing of valves on each side of the floating piston. A detailed explanation of the expansion process can be found in prior work [2]. This work described here has remedied operational issues encountered in previous FPE designs. Those challenges involved piston seals, degradation of the piston, piston tracking difficulties, and valve reliability [3]. This work also describes the to-date performance of the expander in a full recuperative cycle that is capable of achieving cryogenic temperatures.

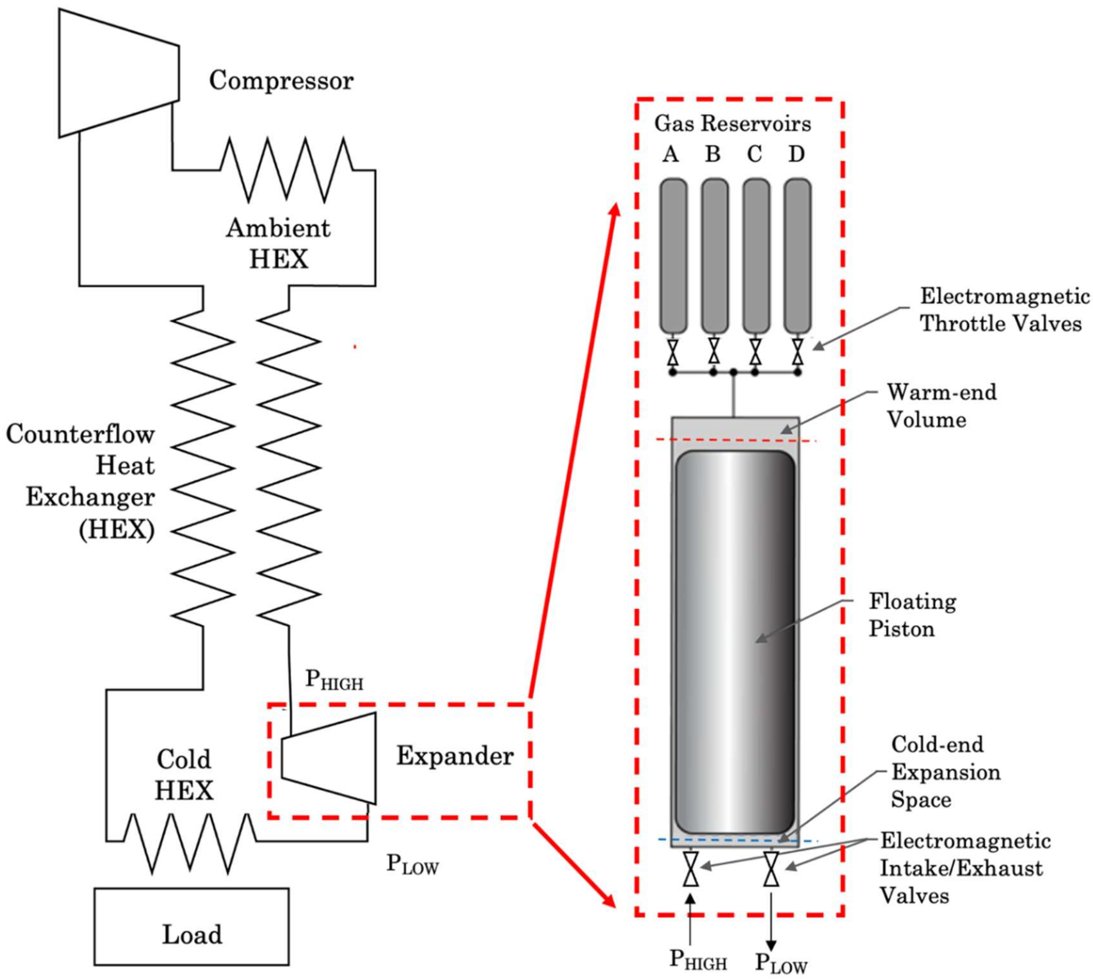

Figure 1. The modified Collins cycle cryocooler with floating piston expander detailed on the right.

2. Experimental Design & Methods

Here we discuss the development of a hermetic Invar-encased carbon-composite piston, the control system, and a cooldown of the single-stage modified Collins refrigerator.

2.1 Mechanical (piston-cylinder material system)

The piston should be light, dimensionally stable, and a thermal insulator. Another constraint is piston control precision to minimize clearance volume without striking the end caps of the floating piston cylinder. A lightweight piston also minimizes vibration. The radial gap width is of the order of 10's of microns to minimize gas leakage along the length of the cylinder and to reduce the heat leak to the cold end. The low Coefficient of Thermal Expansion (CTE) Invar-carbon composite system allows narrower gaps that helps avoid jamming during operation. In addition, to a lightweight piston mass and low CTE, low thermal conductance is a necessity as the piston is exposed to ambient temperatures on one end and cooling load temperatures on the other. The piston has an internal vacuum that insulates between the warm and cold ends of the piston. The thin carbon composite and Invar layers contribute minimally to the heat leak due to their low conductances. Currently, there is no Multi-Layer Insulation (MLI) shielding internal to the piston. The Invar jacket provides a helium barrier as well as an outgassing barrier for the graphite-epoxy composite. The radial gap is 75 microns, shown in Figure 2A, and is consistent with optimal gap calculations that account for shuttle and convective loss mechanisms [4]. The FPE with its associated components can be seen integrated into the vacuum chamber in Figure 2B.

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2.2 Control methodology

Since there are no mechanical linkages to the piston, the accurate motion of the piston requires a real-time control system that precisely controls valve timing and hence piston motion. The electronically-controlled warm-end valves are throttled to limit the floating piston velocities by restricting the gas flows between the warm-end cylinder volume and each of the reservoir volumes. The piston travels quasi-statically in the cylinder at low velocity set by the throttling rate of the gas in and out of the warm-end cylinder volumes. Because of this quasi-static requirement for efficient expansion, the operating frequency of the expander is limited to be below the resonant frequency of the piston/gas-spring system. Typically, the operating frequency for expanders built to date is 1 Hz.

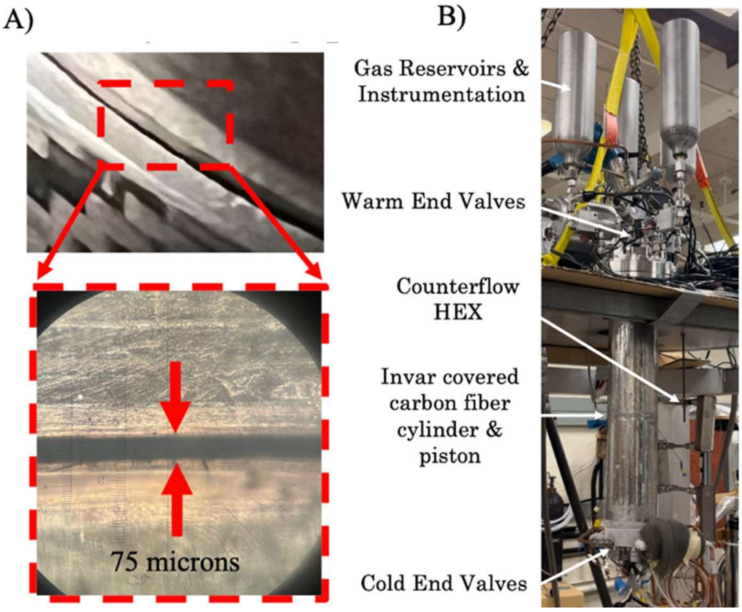

Figure 2. A) Isometric and top-down view of piston-cylinder radial gap of 75 microns. B) Experimental setup of modified Collins cryocooler with integration into vacuum chamber.

2.2.1 Control (hardware and software)

To achieve high efficiency, a real-time control system is needed for valve actuation and precise piston motion control [2]. In addition, the electric power provided to the cold valves can add an unacceptably high heat load to the cold end of the expander. This effect can be reduced significantly by using a time-varying voltage drive to the valve as shown in Figure 3.

In the actuation of a valve, the drive system provides a short "high" voltage pulse that is required to initially open the valve that is then followed by a low "holding" voltage that holds the valve open for duration. Currently, the dissipation drops from 14.4 W, when the power supply provides full voltage to the valves throughout the open duration, to 3.4 W when the stepped voltage pulse control is used. The current pulse control scheme has not yet been fully optimized and the valve power dissipation is expected to be further reduced in the future.

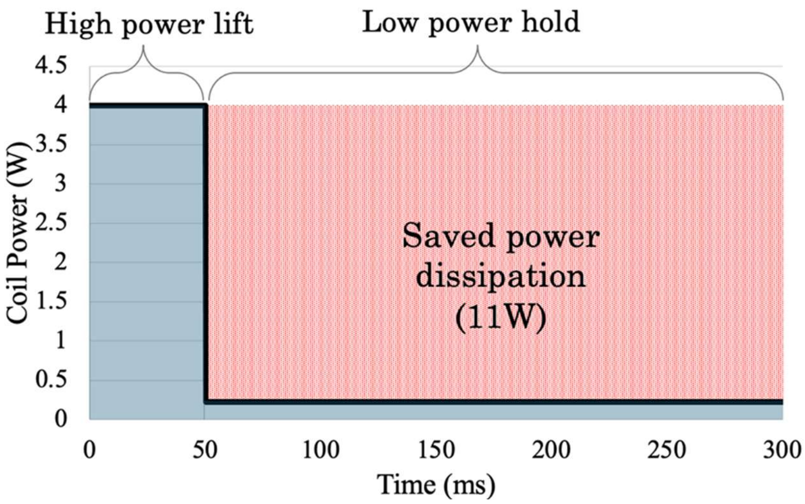

Figure 3. Cold valve power management strategy with sequential high-power lift and low-power hold modes.

3. Results and discussion

A cryogenic prototype test expander was integrated into a vacuum chamber with recuperative heat exchanger as shown in Figure 2B. The FPE expander was placed into a vacuum chamber and operated with a helium working fluid. The resulting cooldown curve (gas outlet temperature vs. time) is shown in Figure 4. The non-smooth behavior of the curve for times less than 0.75 hours can be attributed to the manual adjustment of throttle valves between the pressure reservoirs and the warm cylinder space. The inlet pressure was 7.8 barg and outlet pressure was 3.1 barg which corresponds to a pressure ratio of 2.5:1. The system cooled to 189.7 K. Unfortunately, the system developed a large helium leak to the vacuum space as it cooled. The helium gas in the vacuum space thermally loaded the cryocooler, severely limiting the cryocooler's ultimate temperature.

The occurrence of this leak provided an opportunity to test the robustness of the control system. One of the requirements of the control system is maintaining the distribution of pressures between the compressor discharge and suction pressures. Figure 5 is a plot of the pressures in the four pressure reservoirs as a function of time. Initially, at zero time, the reservoirs are set to four pressures distributed between the anticipated compressor suction and discharge temperatures. As the system runs, these pressures are changed to steady state pressures that are governed by the control algorithm. At 0.3 hours, the leak to the vacuum space becomes significant and the helium in the "closed loop" of the cryocooler begins to leak into the vacuum space. The average pressure of the helium in the closed loop begins to drop and the pressure in the reservoirs remain distributed and track with the decreasing average pressure. At 1.2 hours, helium was constantly introduced into the system to maintain a constant average pressure in the cryocooler as it operated. Once again, the control system redistributed the entering gas into each of the reservoirs while continuously operating the expander. Previous modified Collins control systems have not exhibited this robustness.

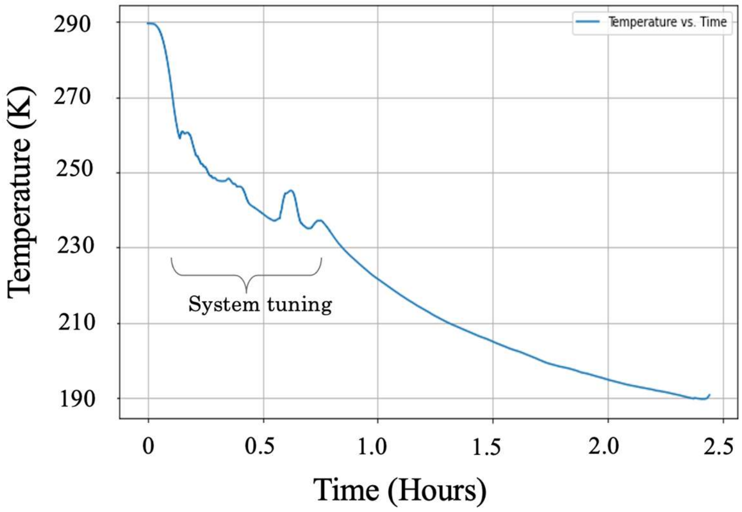

Figure 4. Initial cooldown plot versus time of recuperatively Collins expander with minimum temperature of 189.7 K at a pressure ratio of 2.5:1.

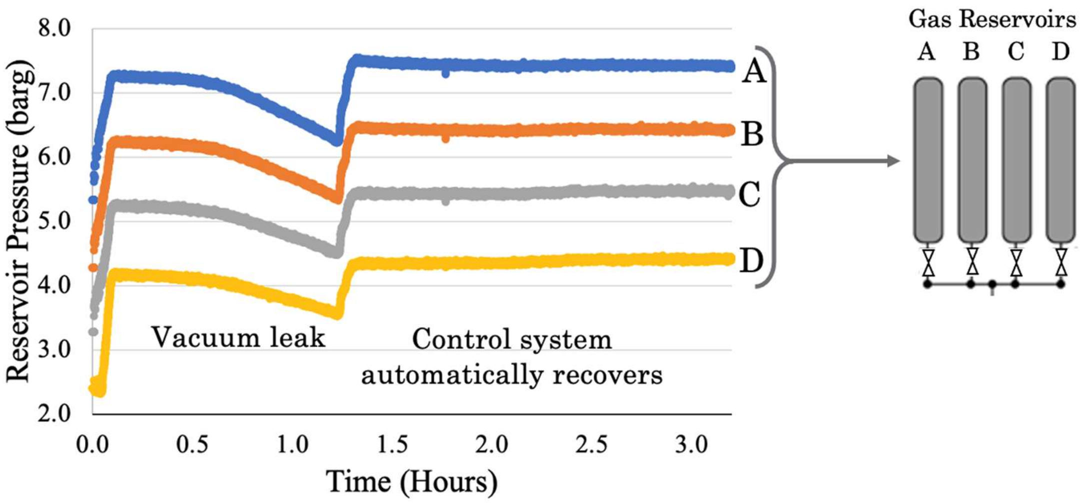

Figure 5. Reservoir pressures vs time for cryogenic operation. Note that the control system automatically recovers with a decrease in system pressure (due to leak) into the vacuum chamber. The system fill begins with additional gas at the 1.2 hour mark and the control system is able to maintain stability.

4. Summary and next steps

There is a need for a low mass and energy efficient cryocoolers capable of cooling propellants for spacecraft. Collins style refrigerators have demonstrated high efficiencies in both medium and large-scale helium liquefiers. This modified cycle uses a floating piston with solenoid valves that reduces mass and complexity of traditional piston expanders. Previous machines of this type had mechanical and control issues that have been addressed in this work. The next step is to demonstrate sub 100 K performance.

5. References

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