Space Cryogenic Circulator

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ABSTRACT

Circulation of cryogenic fluid is a critical technology for cryogenic propellent storage, where it is important to cool the large surface area of the cryogenic storage tank. Furthermore, cryogenic circulation can enable remote cooling of sensitive instruments with low exported vibration by isolating the instrument from the cryocooler with flexible coolant lines.

Lockheed Martin Space has developed a 1.4 kg cryogenic circulator based on a modified pulse tube cryocooler compressor. Lockheed Martin pulse tube compressors have previously operated at cryogenic temperatures as low as 125 K.[1] With Lockheed Martin internal research and development funding, a TRL 6 Mini compressor was retrofitted with newly designed check valves which rectify the oscillating flow. This circulator was tested at ambient temperature, and the measured flow is equal to the piston swept volume times the drive frequency, as expected. The measured flow exceeded 3 standard liters per second helium flow with 90% motor efficiency.

Testing at cryogenic temperature was also performed, and the circulator performed without problems at 90 K. Quantitative testing was not possible because neither the flow meter nor the piston position sensors work at cryogenic temperatures, but some results are presented. These results indicate this cryogenic circulator has sufficient flow to provide 50 W of remote cooling at 90 K with reasonably small thermal gradients.

INTRODUCTION

Cold gas circulation provides remote cooling when the circulating gas is colder than the temperature of the object being cooled. The available heat lift is $Q = m\,C_P\,\Delta T$ where m is the mass flow rate in g/s, C_P is the specific heat in J/gK and ΔT is the temperature difference in K between the outlet and inlet temperature of the circulating gas after heat is extracted from the cryogenic device. An efficient cryogenic circulator requires high mass flow which minimizes ΔT.

This paper describes the development of a cold gas circulator utilizing the space grade compressor and motor modules from a Lockheed Martin Mini cryocooler,[2] with an added pair of check valves to produce a circulating cold gas flow for remote cooling. The objective of the initial work in 2019 was to demonstrate the feasibility of the hardware configuration, while the objective of the 2020 follow-on work was to achieve a technology readiness level (TRL) of five and demonstrate end-to-end performance of the remote cooling loop. The 2019 effort utilized an existing TRL 6 compressor with a separate external check valve assembly, while the 2020 effort designed and built a dedicated space-configuration circulator with integrated check valves.

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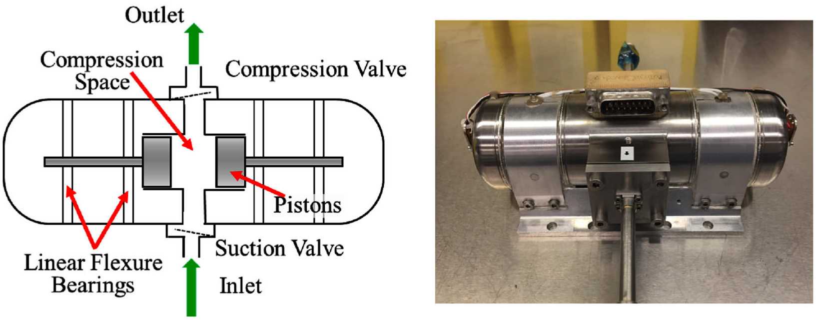

Figure 1. Space Cryogenic Circulator, based on a proven long-life pulse tube cryocooler compressor which had previously demonstrated operation at cryogenic temperature.

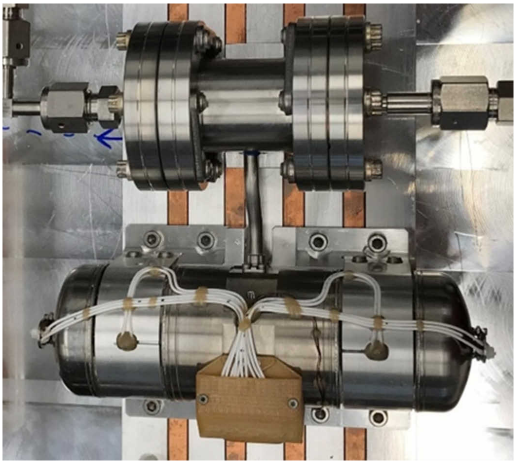

Figure 2. Phase 1 (2019) Circulator Configuration. The TRL 6 Mini compressor (bottom) is connected to a separate check valve assembly (top).

The use of check valves to produce a steady flow with Lockheed Martin compressors started with the successful development of a Joule-Thomson (J-T) Micro compressor.[3,4] For the cryogenic circulator the overall check valve design was similar to that of the J-T but scaled up in size to accommodate the higher circulator flowrate and lower pressure ratio. The Mini compressor swept volume is such that operating at its resonant frequency of 50 Hz, the volumetric flowrate is 53 cc/s at full stroke. This equates to 0.93 g/s helium or 5.1 g/s neon operating at 500 psia. The objective of the demonstration test is to provide 50 W cooling at 90 K. For higher cooling loads, multiple units can be packaged together.[5] Figure 1 shows schematically the implementation of the check valves and the final unit built in 2020. With 50 W of cooling, the mass flow equates to a temperature difference of about 6 K, so that a cryocooler would need to operate at 84 K in order to provide 50 W of cooling at 90 K.

PHASE 1: DEVELOPMENT (2019)

The phase 1 objective was to demonstrate the operation of the Mini compressor to drive two check valves and generate a high flowrate while operating at 90 K. A Lockheed Martin-owned Mini compressor asset was utilized which has its compression space configured with a single port to attach a transfer line for a split pulse tube cryocooler cold head. For this demonstration, a separate check valve assembly was packaged away from the compressor with a transfer line between the two. The compressor and check valve assembly installed on a Lytron cold plate is shown in Figure 2.

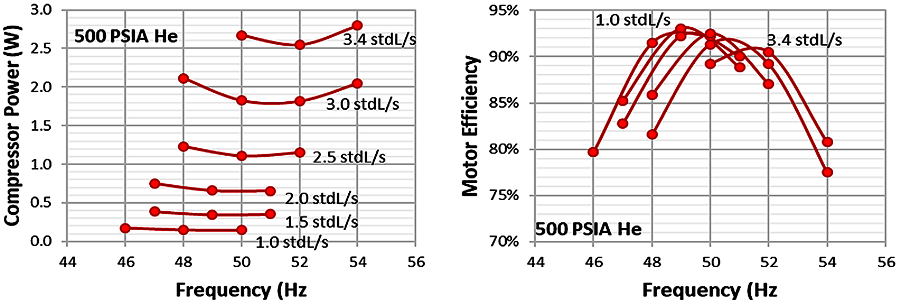

Figure 3. Ambient temperature characterization of circulator.

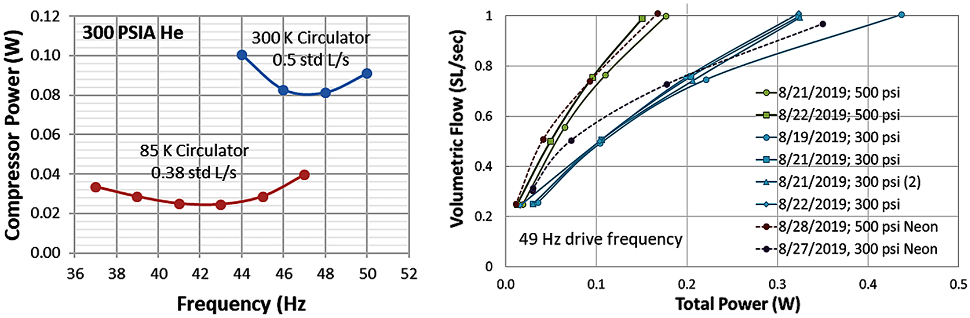

Figure 4. Performance characterization of the circulator at cryogenic temperature.

After assembly of the circulator, its performance at ambient temperature was characterized with 500 PSIA helium gas. Testing included frequency sweeps at different flowrates, to correlate the measured flow rate with the predicted flow rate (piston swept volume × frequency) and measure the motor efficiency. These data are shown in Figure 3, which shows frequency scans with different flow rates. The maximum measured flow rate was 3.4 std liters/second, which was limited not by the circulator stroke but by the gas flow meter. The maximum flow rate will exceed 5 std liters per second at full stroke. The motor efficiency at the optimum frequency was greater than 90% at all flow rates, as expected for a system with low overall electrical input power.

Following ambient temperature characterization, the demonstration circulator and gas flow system were cooled to around 85 K with Lytron plate heat exchangers and liquid nitrogen, to demonstrate cryogenic operation. The piston position sensors do not function at this temperature but were not needed because ambient temperature testing demonstrated that the circulator was operating as expected. However, a flow meter was needed, and the flow meter only operates warm, so it was located outside the thermal vacuum chamber, and the circulating gas was warmed with strip heaters to prevent over-cooling the flow meter. As a result, the flow rate at cryogenic temperature was limited to 1 std liter per second and the circulator needed just a few tenths of a watt of electrical input power. A sample of the data taken at cryogenic temperature with helium and neon at pressures of 300 and 500 psia is shown in Figure 4. The left figure shows a frequency scan with 0.38 std liters/second with the circulator at 85 K. Only 25 mW electrical power was required for this relatively modest flow rate, which would be sufficient to provide several watts of remote cooling with small temperature differential.

The right side of Figure 4 shows volumetric flow in std liters/second as a function of the total electrical power to the circulator. The green solid lines are helium at 500 PSIA, while the light blue solid lines are helium at 300 PSIA. As expected, higher power is required to drive the same absolute volumetric flow at lower pressure because of the lower density and higher actual volumetric flow. The dashed lines are results for neon gas, and are the same as helium, as expected. In all cases, the electrical power was just a few tenths of a watt. No additional flow resistance was added to the flow circuit, which consisted of about 4 meters of flexible high-pressure tubing.

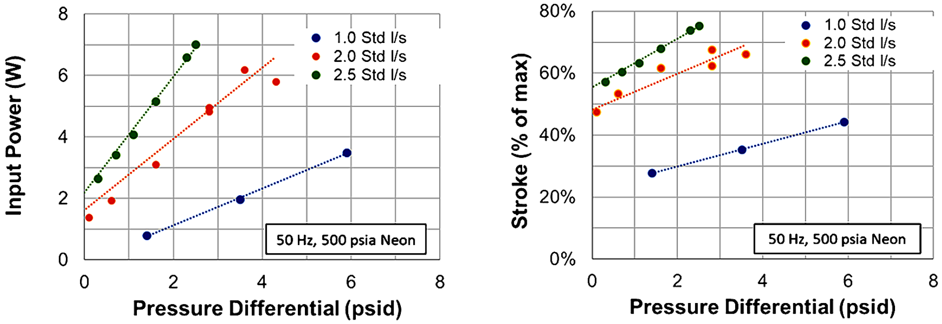

Figure 5. Schematic of complete cold gas circulation system for demonstrating remote cooling

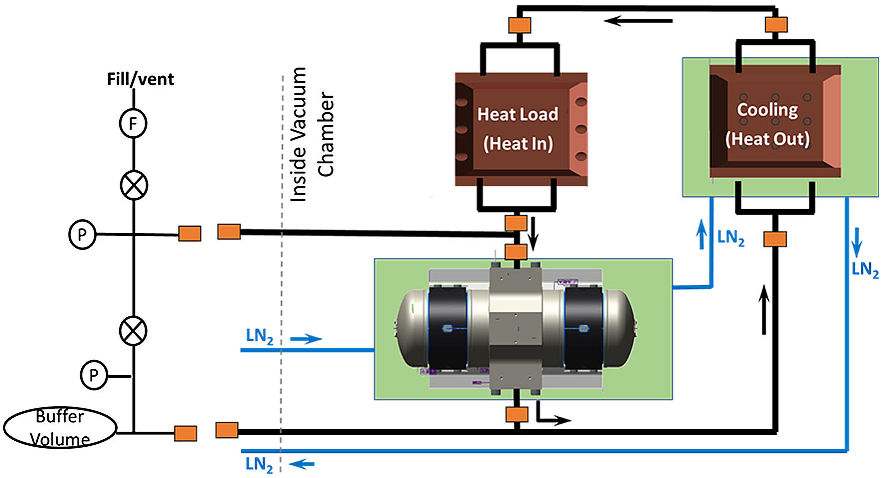

Figure 6. Schematic of complete cold gas circulation system for demonstrating remote cooling.

PHASE 2: DEMONSTRATION (2020)

The phase two objective was two-fold: 1) build a flight-configuration circulator with integrated check valves and mature to TRL 5, and 2) demonstrate remote cooling of a thermal load using circulating cold gas. The welded flight-configuration circulator was shown earlier on the right in Figure 1. This circulator was characterized at ambient temperature, with results very similar to those for the 2019 demonstration circulator. Additional characterization was performed with an added valve used to vary the pressure differential in the flow loop. Results of these tests are shown in Figure 5. The left figure shows the circulator electrical input power and the right figure shows piston stroke as a function of the gas flow differential. For the low pressure differentials expected (< 2 PSID), the electrical power is just a few watts and the position stroke is less than 70% of maximum. This test used neon gas, which is the baseline circulating gas specified by NASA/GRC for cooling cryogenic propellant storage tanks.

A circulator with integrated check valves was fabricated and assembled, along with a remote cooling test facility which included two optimized finned gas heat exchangers. A schematic of the end-to-end test setup is shown in Figure 6. A liquid nitrogen cold sink is used to remove the heat, mimicking the cooling to be eventually provided by a high power cryocooler. These cold sinks are shown by the green shaded rectangles and LN_2 flow lines in Figure 6. Two pressure ports located outside of the vacuum chamber allow measurement of the pressure differential required to maintain flowrate. No cryogenic flow meter was used, and the entire gas loop was cold. Most of the thermometers are thermocouples.

A compact heat exchanger was designed to add and remove the heat from the gas stream. The heat exchanger was optimized to efficiently exchange 50W with 500 psia neon flowing at 4 g/s. The optimization was to minimize the mass of the heat exchanger and the ΔT and ΔP of the gas flow, while being configured

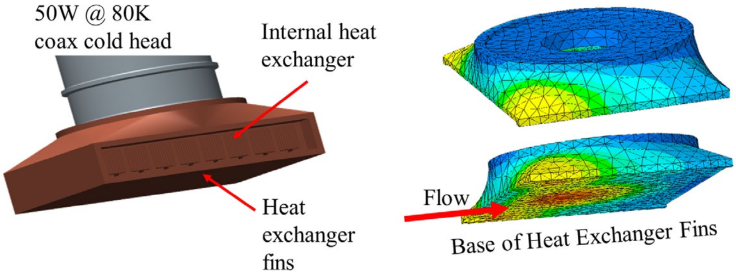

Figure 7. Internal finned heat exchanger integral with the cold tip of a coaxial pulse tube cryocooler. The calculated temperature differential across the cold flange is less than 2 K with 50 W heat exchange.

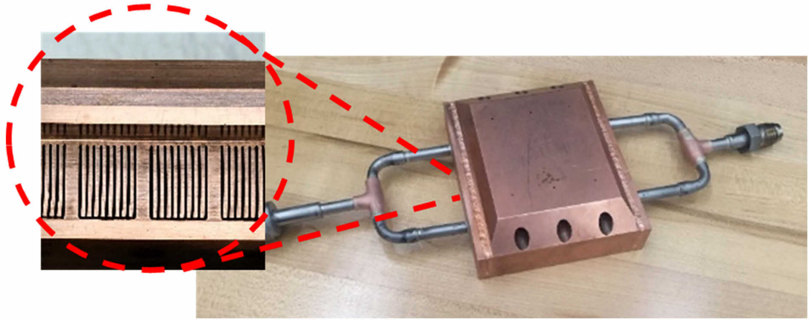

Figure 8. Finned heat exchangers used to introduce and remove heat from the circulating gas. The finned structure can be seen on the left, which shows some of the 72 gas channels. The welded heat exchange with manifolds is shown on the right.

to package on the end of a pulse tube cryocooler cold tip. A finned channel heat exchanger integral to a pulse tube cold head was selected. Five dimensions were optimized as part of the design: the three rectangular dimensions of the block, as well as the fin and gas gap thicknesses.

The design of the heat exchanger integral to a pulse tube cryocooler cold head is shown in Figure 7. The heat exchanger is designed for 7 MPa (1000 psi) internal pressure and is comprised of 72 parallel flow channels.[5]

The efficiency of the fins is calculated based on geometry of the flow passage and conductivity of the material. Fin efficiency calculated was 90% and was used to optimize the packing of the fins and size of the heat exchanger. A thermal model of the integral cold head and heat exchanger was also performed to determine the thermal gradient between the base of the fins and the internal region of the pulse tube where the heat is removed. Parameters for the model were set to mimic the loads the cold head would see to the integral heat exchanger. The results show a two degree gradient from the base of the fins to the internal heat exchanger of the cryocooler cold head. The heat exchanger material is copper which results in a fairly high mass that the pulse tube was analyzed to support under launch loads.

For testing remote cooling, a liquid nitrogen cold plate was attached to one heat exchanger to simulate the cooling provided by a cryocooler. Silver-filled epoxy was used as highly conductive interface between the cold plate and the heat exchanger to mimic the high conductance of an integral pulse tube cold tip + fin heat exchanger. A second identical heat exchanger was used to introduce the 50 W heat into the gas stream to simulate the cooling which will be provided to the cryogenic propellent tank. Photos of the as-built heat exchangers are shown in Figure 8. The holes in the block are used to install cartridge heater elements. Figure 9 shows the completed flow loop.

The performance testing with this flow loop has been limited to date with neon at 500 psia. Characteristic data are initially taken at 150 K, since this is the lowest temperature at which the piston position sensors operate. Relationships between input power, pressure head, and flow determined by stroke are recorded.

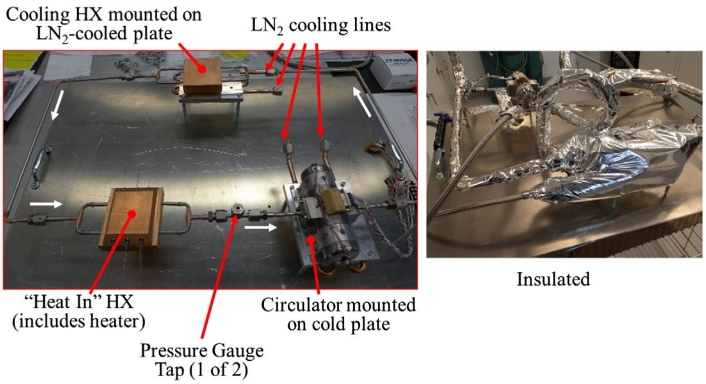

Figure 9. Demonstration of remote cooling. The circulator in the bottom right drives gas flow through the loop which is cooled with liquid nitrogen at the primary heat exchange at the top, and heated with cartridge heaters at the heat exchanger at the bottom left.

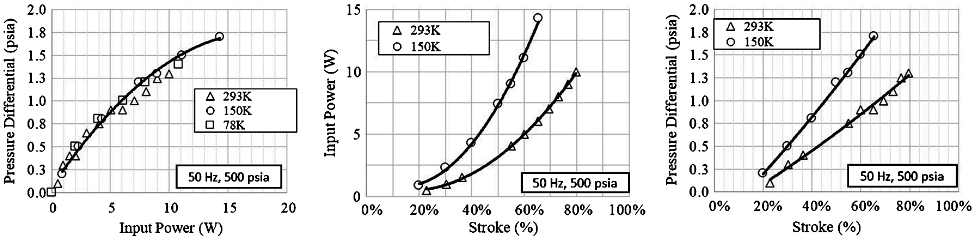

Figure 10. Characteristic of the flow loop as cooled to operating temperature. Data taken at 50 Hz which is not optimum operating condition that is determined with frequency sweeps.

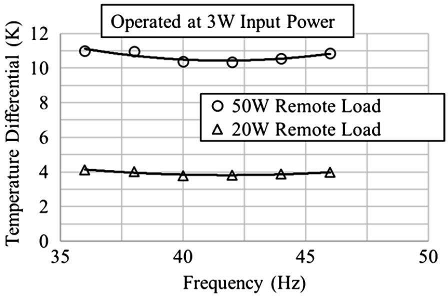

Figure 11. Frequency sweep data of the remote cooling system operating in the 80-90K range. Data shows an optimum operating condition with minimum temperature differential at approximately 40 Hz.

Subsequently data were taken at 80-90 K but without position sensors. Figure 10 shows a set of data while operating at 50 Hz. Operating at constant frequency and pressure results in an increase in input power as the temperature is lowered; this also results in an increase in pressure differential across the circulator. Similar data are recorded over a range of drive frequencies to determine optimum operating parameters, which vary with operating conditions.

Testing of remote cooling proceeded to the range of 80-90 K. One objective of a remote cooling system is to maximize the cryocooler operating temperature at the cold heat exchanger to re-cool the gas and take advantage of better cryocooler performance. This is characterized by minimizing the temperature difference between the outlet of the gas from the load to the gas leaving the cold heat exchanger.

A frequency sweep is shown in Figure 11 performed with 20 and 50W remote loads with only 3W of input power to the circulator. The frequency to achieve a minimum temperature difference is closer to 40 Hz and subsequent testing is performed at this frequency.

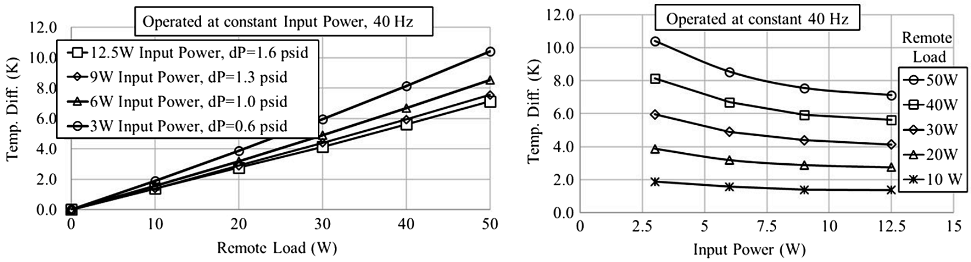

Figure 12. Performance of the remote flow loop with up to a 50W load. Data showed that flowrate appears to be constant at a fixed input power over the range of remote loads up to 50W.

The overall performance of the remote flow loop is shown in Figure 12. The graph on the left shows the temperature difference with various remote loads. The data showed that at a fixed input power the flowrate appeared to be fairly constant and independent of the remote load. The measured pressure differential across the circulator remained constant thus inferring that the flowrate was constant. Therefore, as the input power is lowered, the temperature difference increases in order to remove the load as shown in the figure.

No issues have arisen to date with the check valves for which a life test is planned.

SUMMARY

This effort successfully designed, fabricated and operated a cryogenic circulator utilizing high technology readiness level (TRL) Mini cryocooler motor modules with a set of check valves. An end-to-end remote cooling flow loop was fabricated and tested to show operation with the circulator and a heat exchanger for a cryocooler cold head to remove the transported heat. Tests to date have shown remote cooling up to 50 W at 90 K. The test demonstrated component/system validation in a relevant environment achieving a TRL 5.

ACKNOWLEDGMENT

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