JT Micro Compressor Test Results

J.R. Olson, P. Champagne, E. Roth, T. Nast

Advanced Technology Center, Lockheed Martin Space Systems
Palo Alto, CA 94304, USA

ABSTRACT

We report the results of operational testing of a 200 gram closed-cycle Joule-Thomson Micro Compressor. This unique compressor is a modified version of our TRL 6 Pulse Tube Micro Compressor, using the same Oxford-style flexure bearing and clearance seal architecture common in highly reliable long life cryocoolers. The compressor is capable of delivering closed-loop dc gas flow with a high pressure ratio, suitable for driving a Joule-Thomson cryocooler.

The Joule-Thomson compressor was operated while charged with nitrogen gas at pressures ranging from 50 PSI to 150 PSI. Output pressure ratios were varied from 2:1 to as high as 7:1 at different gas flow values. In all cases, the compressor operated smoothly, without any indication of unusual mechanical or gas dynamics such as instabilities or excessive gas backflow through the check valves. Power conversion efficiency was calculated based on the theoretical power required to deliver specific pressures and gas flows vs. the measured compressor power. Conversion efficiency ranged from 15% for the highest pressure ratios, to greater than 30% for lower pressure ratios. These values are in close agreement with the expected efficiency of approximately 25%, based on predicted check valve, clearance seal, and surface pressurization losses.

INTRODUCTION

Joule-Thomson (JT) cryocoolers have only been used in space for specialized low-temperature applications, such as the 6 K cooling stage for the MIRI cryocooler [1]. The primary reasons for this are the complexity of the JT compressor and cooler, and the low JT cooler efficiency at the temperatures required by typical cryogenic applications.

The recent development [2,3] of mid-wave infrared focal planes operating at 120-150 K temperature, rather than 80 K as required by traditional InSb detectors, allows JT coolers to use optimized high-performance gas mixtures, rather than pure nitrogen, as the working fluid. JT coolers using optimized gas mixtures can potentially have higher efficiency than Stirling-cycle coolers.

Lockheed Martin reported last year [4] on the development of a closed-cycle JT micro compressor suitable for long-life cryogenic applications, including space applications. That report described the design of the JT compressor. To briefly summarize, the Pulse Tube micro compressor previously qualified to TRL 6 [5, 6] was modified for use as a JT compressor. While retaining the same flexure bearing, clearance seal, long life compressor architecture, two

Cryocoolers 19, edited by S.D. Miller and R.G. Ross, Jr.

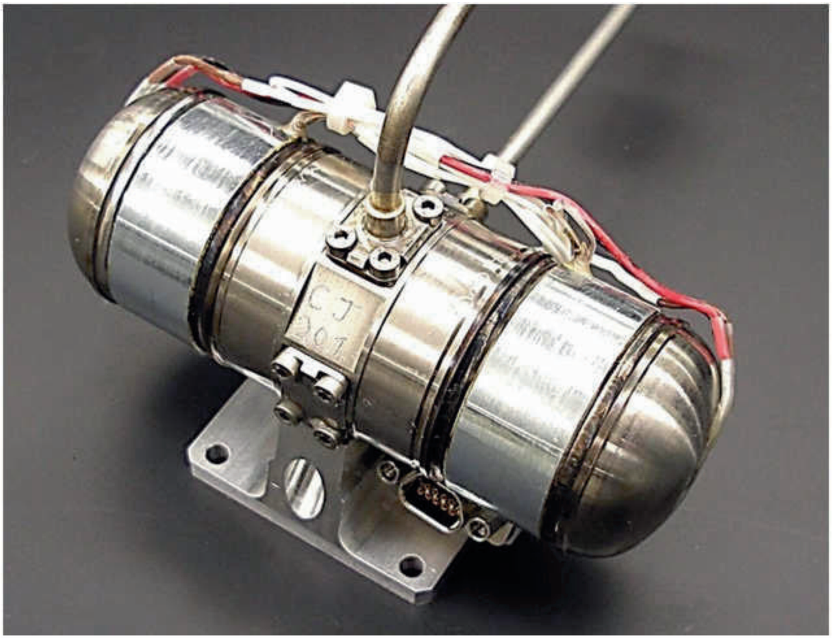

Figure 1. Lockheed Martin Joule-Thomson micro compressor. This 200 gram compressor has piston architecture identical to the pulse tube compressor previously qualified to TRL 6, but includes check valves to rectify the ac pressure to generate the dc gas flow needed by the JT cryocooler valves to rectify the ac pressure to generate the dc gas flow needed by the JT cryocooler.

check valves were added to each compressor module in order to convert the ac pressure wave into a continuous dc flow. By operating these two modules in series, Lockheed Martin was able to achieve pressure ratios suitable for a JT cryocooler, while retaining the low exported vibration inherent in compressors with back-to-back piston modules. This compressor is shown in Figure 1.

The design of an efficient JT cryocooler using gas mixtures is a complex problem, because the gas constituents and mixing ratios of the optimum gas mixture are functions of the high and low pressures of the JT cooler, but the efficiency of the JT compressor is also a function of the high and low pressures. This optimization is more complicated than Stirling and Pulse Tube coolers because of the very high pressure ratios in the JT compressor. In order to achieve a pressure ratio of 4:1, it is necessary that each module have a pressure ratio of 2:1, whereas the pressure ratio in Stirling and Pulse Tube coolers is generally less than 1.3:1. The secondary compressor losses from surface pressurization in the compression spaces and leakage in the piston clearance seals scale with the square of the pressure ratio, causing these losses to dominate the motor i^2R coil losses, which are typically the largest loss in a Stirling or pulse tube cooler.

In order to facilitate future JT cooler optimization, extensive compressor testing was performed on the JT compressor described in [4], so that future gas mixture studies can take the compressor efficiency into account.

JT COMPRESSOR TESTING

Test Setup

The JT compressor was connected to a closed-loop gas system and instrumented with pressure sensors and a calibrated gas flow meter, as shown in Figure 2. A metering valve was

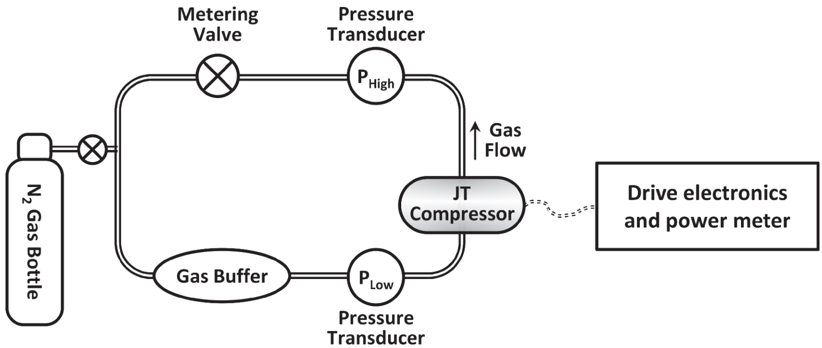

Figure 2. JT compressor test setup. The low pressure is adjustable with the nitrogen gas bottle, and the high pressure and gas flow are adjustable by varying the compressor input power and the metering valve. The compressor power, current and voltage are monitored with a wattmeter.

used to set the desired gas flow rate. The gas volume in the high pressure side was minimized, and a gas buffer was included in the low pressure side in order to decrease the response time of the system to changes in compressor operation. The compressor and gas loop were maintained at ambient temperature with air cooling. All testing was performed with nitrogen working gas.

TEST RESULTS

JT Compressor testing was performed with low pressure values of 50, 75, 100, and 150 PSIA, and pressure ratios ranging from 2:1 to as high as 7:1, with varying amounts of nitrogen gas flow. For each operating point (with a specific low pressure, pressure ratio, and gas flow rate), a frequency scan was conducted to determine the optimum operating frequency. One representative frequency scan is shown in Figure 3, for a low pressure of 100 PSIA, a pressure ratio of 4:1, and a flow rate of zero. The compressor electrical input power is shown in the figure on the left, and includes both the total electrical input power, and the individual input powers for each compressor module. It can be seen that the total compressor power has a weak minimum, in this case at 106 Hz, and that the two compressor modules have minima at slightly different frequencies, 102 and 110 Hz. The figure on the right shows the PV power, calculated by subtracting the motor i^2R loss from the electrical power. The PV power in this case, and

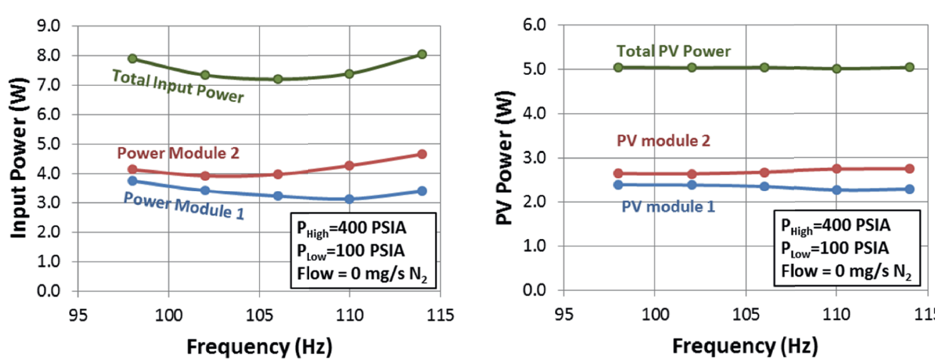

Figure 3. Measured frequency scan for JT compressor operating at 100 PSIA low pressure, 400 PSIA high pressure, with no gas flow. These representative data show that the compressor electrical input power has a weak minimum at 106 Hz (left plot), whereas the individual compressor modules have individual minima at 102 and 110 Hz. The specific frequencies corresponding to these minima vary with low and high operating pressure. The PV power (total, and for each individual module) is independent of frequency.

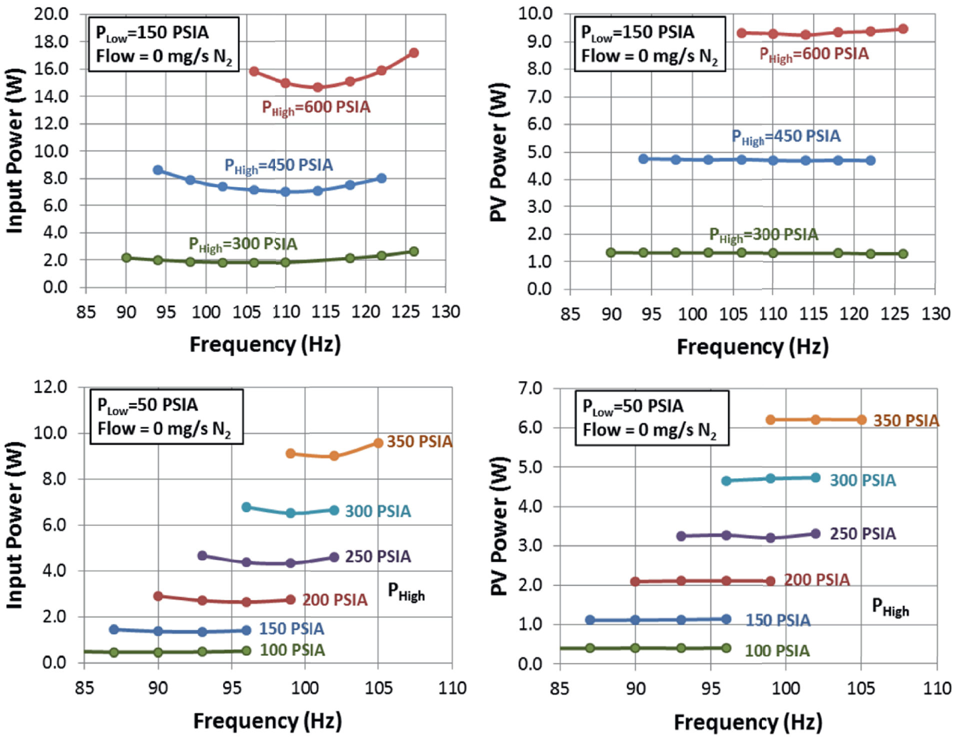

Figure 4. Other measured frequency scans for JT compressor operating at 150 PSIA low pressure (top figures) and 50 PSIA low pressure (bottom figures). The optimum frequency (minimum input power) increases as the pressure ratio increases, because of the effect of the gas spring. As in Figure 3, the PV power is independent of frequency.

indeed in every case measured in this study, is very nearly independent of frequency. This is an indication that there is no detrimental dynamics present in the check valves, which might be expected to lead to frequency-dependent backflow losses.

Several other frequency scans, all still with zero gas flow, are shown in Figure 4. The two upper figures are the total electrical input power and PV Power for 150 PSIA low pressure, with pressure ratios of 2:1, 3:1 and 4:1. The two lower figures are for 50 PSIA low pressure, and pressure ratios ranging from 2:1 to 7:1. As before, the PV power is independent of frequency. As one might expect, as the pressure ratio increases, the optimum frequency also increases, because of the increasing gas spring effect.

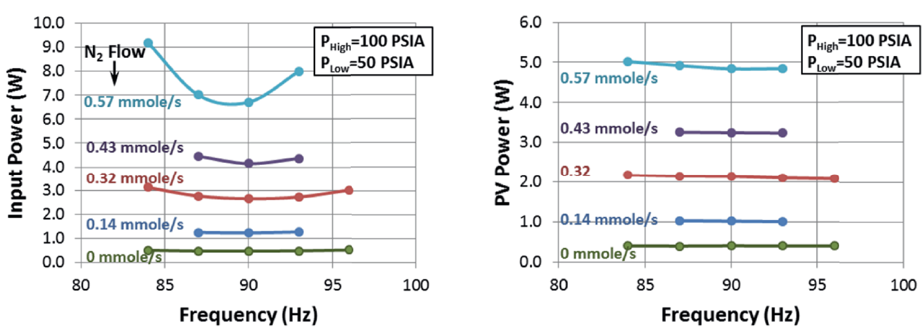

Figure 5. Effect of varying the gas flow, for one representative case (50 PSIA low pressure, 2:1 pressure ratio). As expected, more gas flow requires more input power.

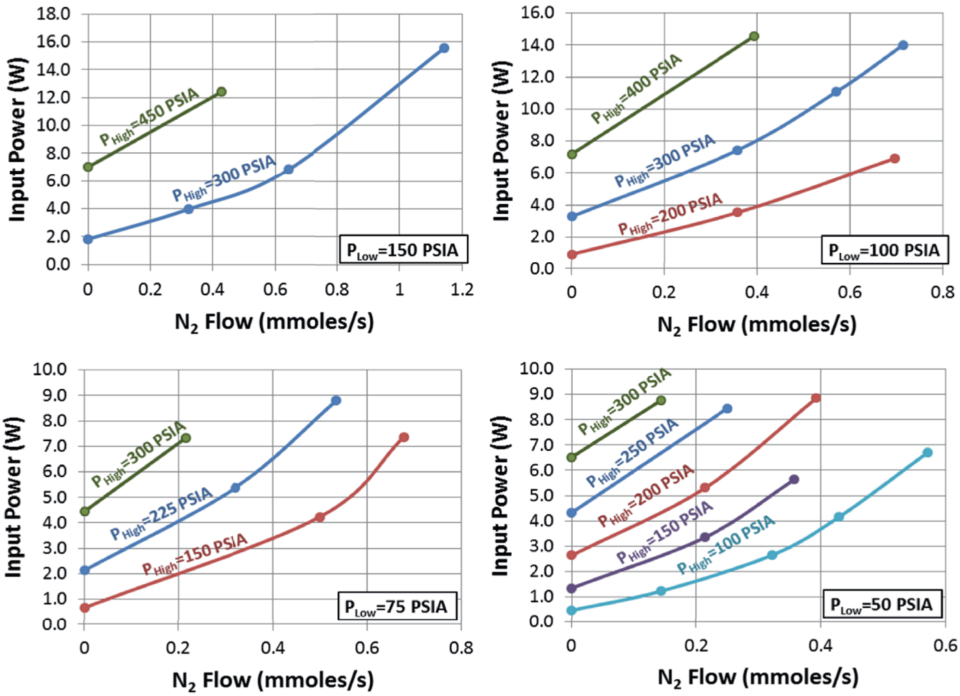

Figure 6. Optimum (minimum) compressor input power for every set of conditions tested in this study. As expected, the input power increases with increasing pressure ratio and increasing gas flow.

The effect of varying the gas flow is shown in Figure 5 for one representative case, with 50 PSIA low pressure, a pressure ratio of 2:1, and nitrogen gas flow varying from zero to 0.57 mmoles/second. As expected, as the gas flow increases while keeping the pressure ratio constant, the input power and PV power increase. As before, the PV power is nearly independent of frequency. The optimum frequency is nearly independent of flow for constant high and low pressures.

From every frequency scan such as those shown in Figure 5, we can extract the minimum input power. These optimum points are shown in Figure 6, for every set of test conditions measured during this study. Low pressures of 50, 75, 100 and 150 PSIA are shown, with nitrogen flow varying from zero up to nearly the maximum capacity of the compressor. The input power is a strong function of the pressures and flow values. For the cases of 100 and 150 PSIA low pressure, the maximum flow was limited by the compressor power we were willing to apply when fan-cooling the compressor. With good conductive cooling, we could achieve somewhat higher flow rates. For the cases of 50 and 75 PSIA low pressures, we were limited by the swept volume capability of the compressor. As expected, the input power increases as the pressure ratio and the gas flow increase.

In order to make the best use of these measurements, especially when assessing potential JT gas mixtures, it is useful to compare the measured compressor power with the ideal compressor power that one can calculate for ideal, lossless, isothermal compression. This ideal compressor power is given by

$$\text{Ideal Compressor Power} = \dot{m} C_P T_0 \left[\left(\frac{P_{High}}{P_{Low}} \right)^{1-\frac{1}{\gamma}} - 1 \right] \tag{1}$$

where $\dot{m}$ is the mass flow (g/s), C_P is the gas specific heat (J/g-K), T_0 is the ambient temperature (K), P_{High} and P_{Low} are the operating pressures, and γ is the ratio of specific heats.

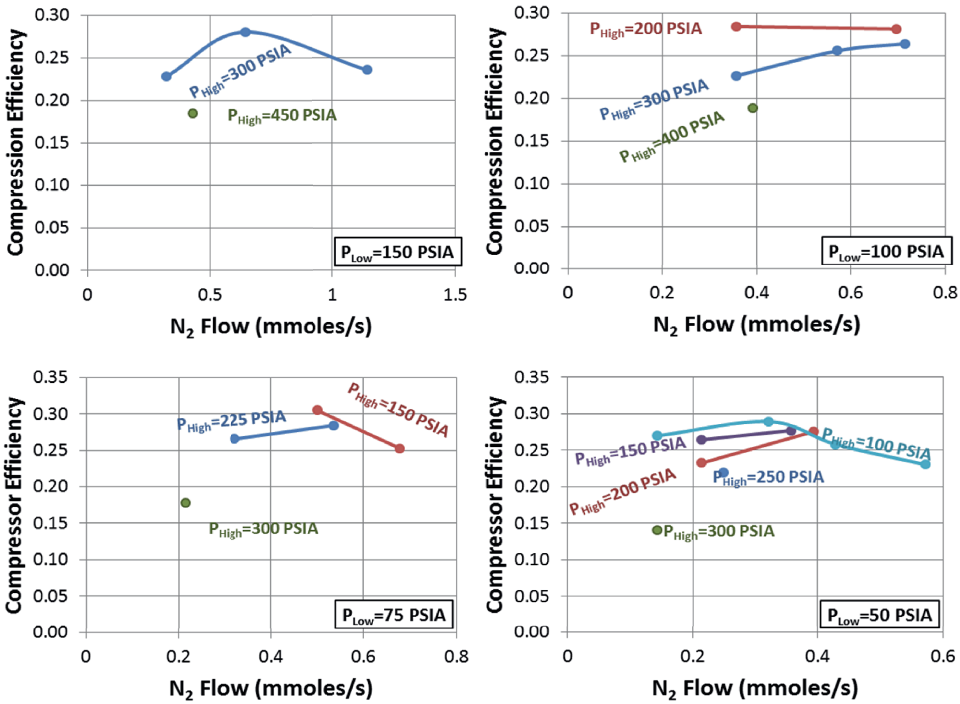

Figure 7. Measured compressor efficiency, calculated by dividing the ideal lossless isothermal compressor power by the measured compressor input power. The measured compressor efficiency of 20-30% is high enough that a JT cryocooler with an optimized gas mixture can have a cryocooler efficiency comparable to a Stirling or pulse tube cooler at 150 K cold tip temperature.

We calculate the compressor efficiency for every point in Figure 6 by dividing the ideal compressor power by the measured compressor power. The calculated compressor efficiencies are shown in Figure 7. The compression efficiency is in the range of 20-30% for most data points. This efficiency includes all the losses in the compressor, including motor i^2R coil losses, piston clearance seal and surface pressurization losses, and losses associated with the check valves and gas flow passages.

DISCUSSION AND FUTURE WORK

The data shown in Figure 7 show that the Lockheed Martin JT micro compressor is capable of achieving a compression efficiency that is 20-30% of the ideal compression efficiency over a range of pressure ratios from 2:1 to as high as 5:1, with generally higher efficiency at lower pressure ratio and lower values of the low operating pressure. According to preliminary gas mixture analyses, this compressor performance is sufficient to allow a closed-cycle JT cooler to have an efficiency comparable to a Stirling or pulse tube cryocooler when operating at 150 K. Work is ongoing to develop a high-performance, low-cost counterflow heat exchanger for a JT cooler with comparable performance to the cooler described in [5]. Future work is planned to develop the optimized gas mixture.

ACKNOWLEDGMENT

This work was supported by the United States Air Force through CU Aerospace STTR Phase II Prime Contract # FA9550-15-C-0019 “Microvascular Composites for Novel Thermal Management Devices.” The authors wish to thank the CU Aerospace principal investigator Dr. Chris Mangun, and the AFRL program manager Dr. Byung-Lip "Les" Lee for their helpful interactions.

The compressor tested in this work is the property of Santa Barbara Focalplane. The authors wish to thank Vince Loung and Elna Saito for allowing the use of this hardware during this STTR program.

REFERENCES

1. Petach, M. and Michaelian, M., "Mid InfraRed Instrument (MIRI) Cooler Cold Head Assembly Acceptance Testing and Characterization," *Cryocoolers* 18, ICC Press, Boulder, Colorado (2014), pp. 11-17.
2. Ramirez, D.A. et al., "High-operating temperature MWIR unipolar barrier photodetectors based on strained layer superlattices," Proc. SPIE 945 1, Infrared Technology and Applications XLI, 945 113 (2015); doi: 10.1117/12.2176908.
3. Klipstein, P. et al., "Reducing the cooling requirements of mid-wave IR detector arrays," SPIE Newsroom, (2011), doi: 10.1117/2.1201111.003919.
4. Champagne, P., et al., "Development of a J-T Micro Compressor," IOP Conf. Series: Materials Science and Engineering 101 (2015) 012009.
5. Nast, T.C., Roth, E., Olson, J.R., Champagne, P., Frank, D., "Qualification of Lockheed Martin Micro Pulse Tube Cryocooler to TRL 6," *Cryocoolers* 18, ICC Press, Boulder, Colorado (2014), pp. 45-50.
6. Olson, J.R., Kaldas, G., Champagne, P., Roth, E. and Nast, T., "MatISSE Microcryocooler," IOP Conf. Series: Materials Science and Engineering 101 (2015) 012025.