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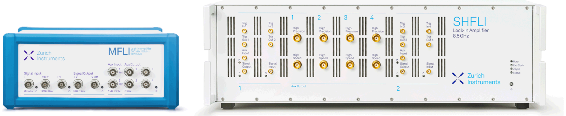

VERY HIGH CAPACITY AEROSPACE CRYOCOOLER

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ABSTRACT

Long-term cryogenic propellant storage requires mechanical cryocoolers to maintain zero or very low cryogen boil-off rates. Very large cryogen tanks such as those proposed for orbital fuel depots may require cryocoolers with very high cooling capacity. In-situ resource generation and storage of oxygen and methane on Mars also requires high capacity cryocoolers, and low mass is extremely desirable for planetary missions because of the cost associated with landing mass on the surface of another planet. Lockheed Martin's Advanced Technology Center has developed a high capacity low mass aerospace cryocooler with very high power density. This 7 kg pulse tube cryocooler can provide 20 W of cooling at 70 K while rejecting heat at 300 K. This large cooling capability could also be used to cool large optical structures or other devices with high heat loads. Testing of the cooler with a secondary heat exchanger attached to the pulse tube was also conducted, and results are discussed.

KEYWORDS: Cryocooler, Cryogenic Propellant, Pulse Tube

INTRODUCTION

There are many aerospace cryocooler applications which require very large cooling capacity. Large Earth-staring surveillance satellites may have high heat loads on cold optical components. Zero boil-off cryogen storage tanks such as those proposed for an orbital fuel depot require a cooled tank or shield with high parasitic heat loads. In-situ resource generation plants for liquefying and storing liquid oxygen and liquid methane on Mars may require large cooling capacity, and furthermore must be very low mass because of the cost of landing mass on the Martian surface.

With Lockheed Martin Space Systems Company internal research and development (IRAD) funding, the Advanced Technology Center in Palo Alto has developed a high

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power, low mass, long life aerospace cryocooler capable of meeting the needs of many applications requiring large cooling capacity.

DESCRIPTION OF CRYOCOOLER

Coldhead

The high capacity cryocooler coldhead is a robust in-line pulse tube, designed to provide 20 W of cooling at 70 K while rejecting heat at 300 K. This prototype coldhead was designed as a laboratory test cooler for future pulse tube component testing for advanced components such as enhanced heat exchangers, new regenerator materials, and other novel pulse tube concepts.

The coldhead is shown in FIGURE 1. The bolted c-sealed cold flange is in the middle, and has a large Minco resistive heater (not shown) attached to the circumference and a platinum resistance thermometer attached near the pulse tube. The regenerator is below the cold flange, and is obscured by multi-layer insulation. The aftercooler is in a copper flange below the regenerator which forms part of the vacuum seal. The pulse tube is above the cold flange, and is ribbed to prevent buckling while the cooler is under vacuum. The pulse tube warm flange, heat exchanger, and inertance tube are at the top of the pulse tube, and this heat exchanger has a separate cooling water loop so that its temperature can be set independently of the aftercooler temperature.

Compressor

The high capacity cryocooler is driven by a Lockheed Martin M5 Midi compressor. This compressor is shown in FIGURE 2. This compressor is capable of electrical input

FIGURE 1: Prototype high capacity pulse tube coldhead. The regenerator is below the bolted copper cold flange, obscured by MLI. The pulse tube is above the cold flange. The aftercooler is in a copper flange below the regenerator, which forms part of the vacuum seal.

FIGURE 2: Lockheed Martin M5 Midi compressor. This TRL 6 compressor has a mass of 6 kg and an input power capability of 600 W electrical power. During this testing, the compressor demonstrated 75% efficiency with 600 W electrical input power, and 85% efficiency with 200 W electrical input power. A 12-ounce soda can is shown in the background for size comparison.

power in excess of 600 W, with a mass of just 6 kg. During the testing reported in this paper, the compressor was water-cooled with motor module cooling jackets, one of which is visible in the right-hand module in FIGURE 2. For high-power aerospace applications, some additional mass would need to be added for conducting to the heat rejection interface.

The M5 Midi compressor is currently at TRL 6, having undergone qualification testing such as launch vibration survival during a previous program. The compressor demonstrated 75% efficiency during testing with 600 W compressor electrical power, and 85% efficiency with 200 W compressor electrical power.

CRYOCOOLER PERFORMANCE TESTING

Baseline Cooling Performance

Cryocooler testing was conducted with the pulse tube coldhead in an evacuated vacuum chamber and the compressor in air, with a 20 cm long transfer line between them. The pulse tube warm flange formed part of the chamber vacuum seal. The coldhead and the compressor were water-cooled to 300 K. The pulse tube cold tip had a Minco resistive heater, and was limited to approximately 45 W of heater power. The temperature was read with a calibrated platinum resistance thermometer. Input power, current and voltage were measured with a Yokogawa digital power meter.

The measured cooling power as a function of the cold tip temperature and the compressor electrical input power is shown in FIGURE 3. The figure on the left plots the data as a function of compressor electrical power, while the figure on the right shows the same data plotted as a function of the cold tip temperature. The cryocooler operated in a stable condition for compressor power up to 400 W, but for higher input power, the piston motion was occasionally erratic, with coupling between a shift in the piston's center position, and its amplitude. This erratic behavior limited the data we chose to take at high power. For an application requiring power in excess of 400 W, we would install additional mechanical springs to help keep the piston centered. Additional springs would not affect

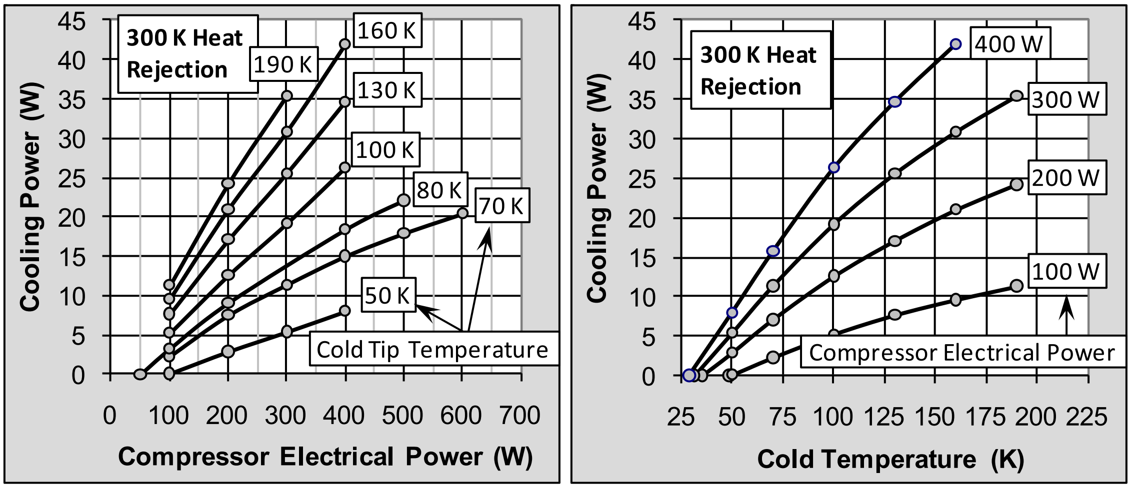

FIGURE 3: Measured cooling power as a function of compressor electrical power and cold tip temperature. The figure on the left plots the data as a function of compressor electrical power, while the figure on the right shows the same data plotted as a function of the cold tip temperature. All data were measured with 300 K heat rejection temperature on the aftercooler and the pulse tube warm heat exchanger.

the compressor resonant frequency appreciably, because the gas spring is greater than the mechanical spring.

The high capacity cooler was able to provide 20 W of cooling power at 70 K with 600 W of compressor electrical power, and 26 W of cooling at 100 K with 400 W of compressor electrical power. The specific power (input power / cooling power) is shown in FIGURE 4. The specific power is good but not great, with 15 W/W at 100 K for example. But this cooler was not designed for maximum efficiency, rather for high power density. Later testing at reduced gas pressure and longer piston stroke achieved 12 W/W at 100 K with 200 W input power.

Several sensitivity trades were also performed. FIGURE 5 shows two of these trades. The figure on the left shows the cooling power as a function of frequency with the cold tip at 70 K and 200 W of compressor electrical power. This is a typical frequency scan; the cooling power decreases by about 10% when the operating frequency is 10% off optimum.

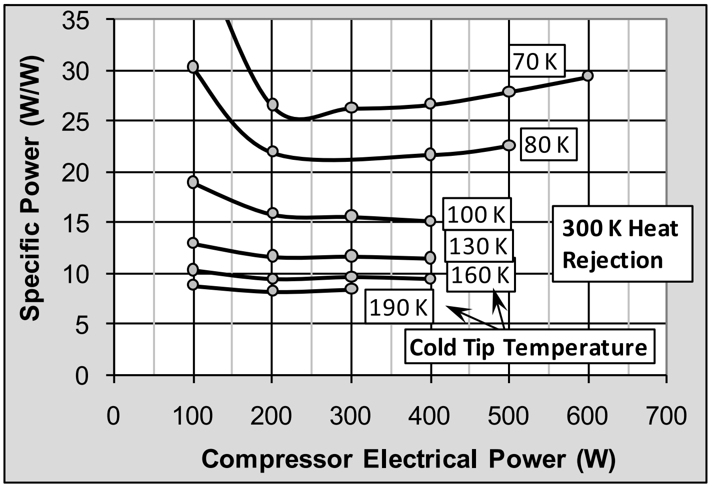

FIGURE 4: Measured cryocooler specific power (electrical input power/cooling power) for the data shown in FIGURE 3. This cooler was not designed for highest efficiency, but for high power density. Later testing with lower gas pressure and longer piston stroke reduced the specific power by about 20%.

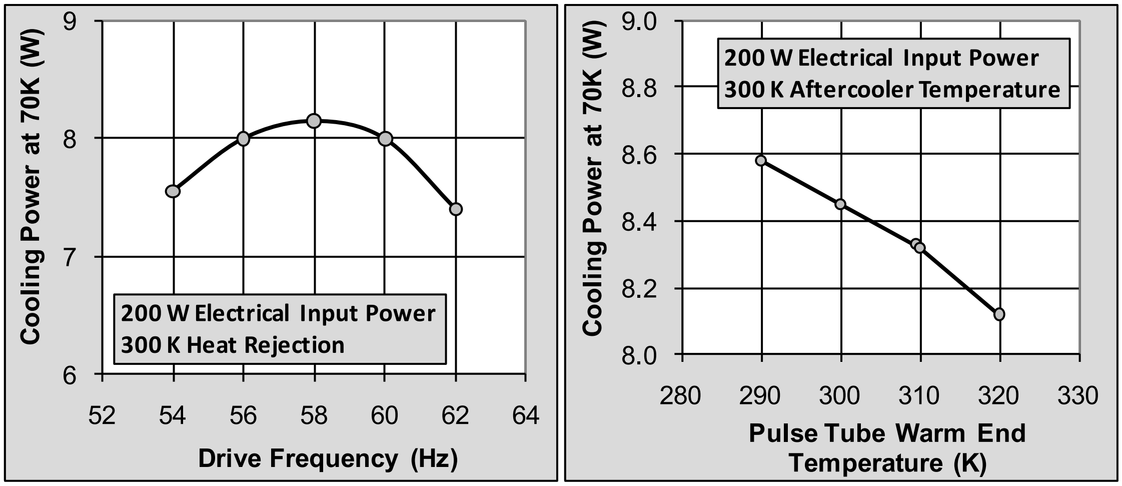

FIGURE 5: Pulse tube performance sensitivity trades. Cooling power as a function of frequency is shown on the left, and is a very typical frequency scan, with approximately 10% of the cooling power lost when the drive frequency is 10% off of optimum. The figure on the right shows the cooling power as a function of the temperature of the warm end of the pulse tube, keeping the aftercooler temperature constant at 300 K. There is only a 5% difference in cooling power when this temperature varies between 290 K and 320 K.

The figure on the right shows the cooling power as a function of the pulse tube warm end heat exchanger, with the cold tip at 70 K and 200 W of compressor electrical power. The primary heat exchanger (aftercooler) temperature was kept at a constant temperature of 300 K. Because this is an in-line pulse tube, both ends of the cooler require heat rejection, and in a real application they need not operate at the same temperature. There is only a weak dependence on the pulse tube warm end temperature, with the cooling power varying by just 5% when the warm end temperature varies from 290 K to 320 K.

Testing With Secondary Pulse Tube Heat Exchanger

Researchers at NIST have reported [1, 2] that the efficiency of a vapor liquefier can be enhanced by extracting some of the heat from the regenerator tube at a higher temperature by flowing the gas down a tube coiled around the regenerator. A researcher at Cryomech performed a similar study [3] with a low-frequency “GM-type” pulse tube cooler, and found that it is advantageous to extract cooling from the pulse tube instead of the regenerator, and that there are cases when some cooling can be extracted with *no impact* on the cooling power of the primary stages.

The notion of getting some “free cooling” at a point on the pulse tube without affecting the primary cooling power was intriguing, and motivated a small IRAD project to add a secondary heater on the pulse tube. Rather than building in a gas flow loop, as was done by the other researchers, we chose simply to add a heater to a single location on the pulse tube, close to the cold end in order to get cooling at a temperature approximately 30-50K warmer than the cold tip. A copper block was machined which fit snugly around the pulse tube circumference and made thermal contact over a contact length of about 3 mm via thermal vacuum grease. The two halves of the copper block were heated with two cartridge heaters, and the temperature of the copper block was measured with a platinum resistance thermometer.

Test results are shown in FIGURE 6 for a variety of operating conditions, with varying frequency, cold tip temperature, input power, and gas pressure as shown in the inset of each figure. In each of the figures, the upper curve is the cooling power of the

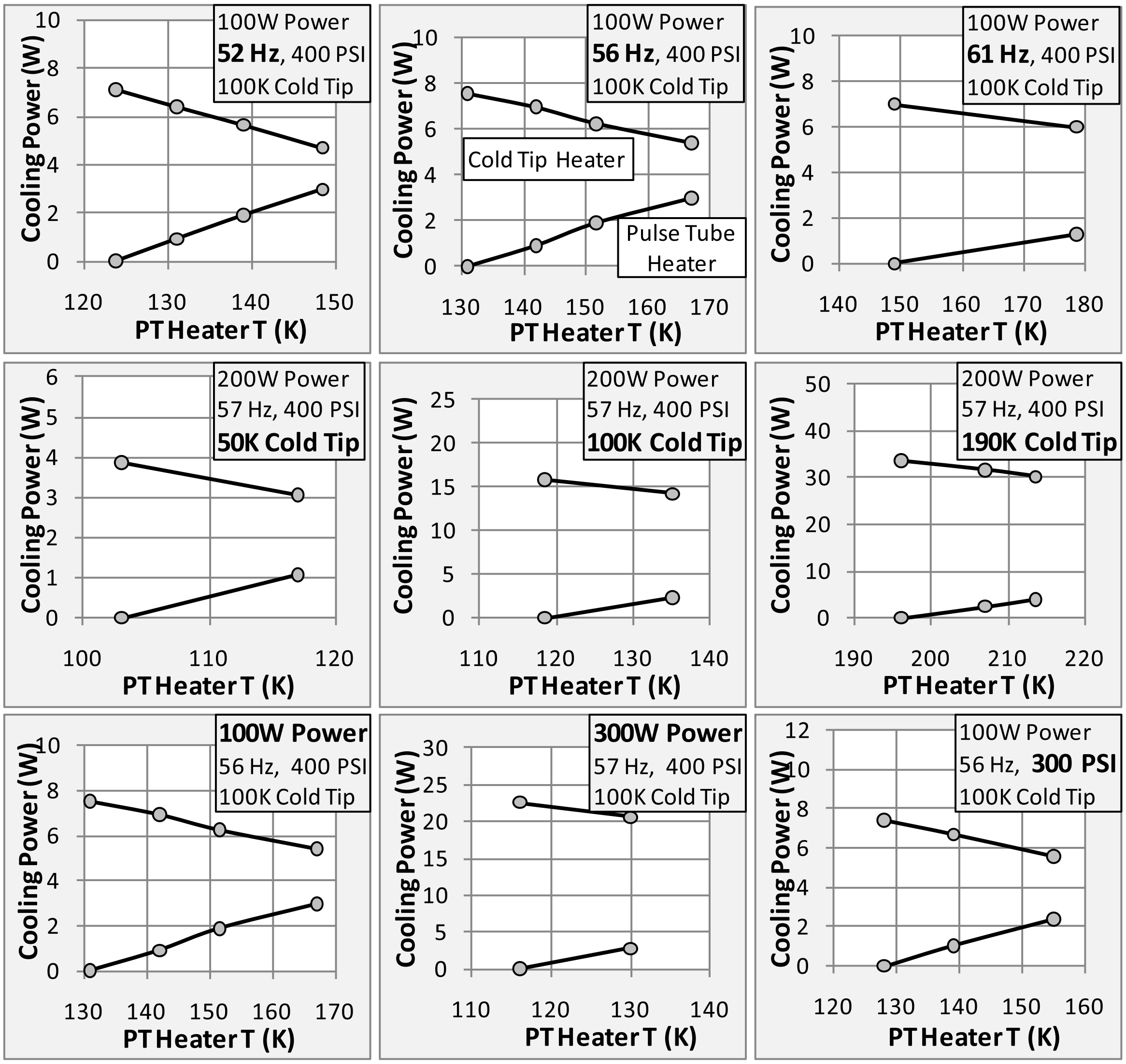

FIGURE 6: Performance testing with a secondary heater mounted to the pulse tube. In all 9 figures, the vertical axis is the cooling power, the horizontal axis is the temperature of the secondary heater on the pulse tube, the top curve is the primary cooling power at the cold tip, and the bottom curve is the cooling power of the secondary pulse tube heater. Tests were performed with varying operating frequency, cold tip temperature, input power, and gas pressure. In all cases, adding heat to the secondary heat exchanger causes a loss of cooling at the primary heat exchanger.

primary cold tip heater (which was held at a constant temperature), and the lower curve is the cooling power of the secondary heater mounted on the pulse tube, which warmed up as more heat was added. The x-axis is the temperature of the secondary pulse tube heater ("PT Heater T").

We measured no "free cooling" for any of the cases tested; in all cases, adding heat to the secondary heater resulted in a decrease in the cooling power of the primary heater. The difference between this cooler and Cryomech's [3] is a mystery. For example, in the figure in the top right (100 W compressor electrical power, 52 Hz, 400 PSI, 100 K cold tip temperature), adding 3 W of heat to the secondary pulse tube heater (at 148 K) resulted in a loss of 2.4 W of cooling at 100 K.

In all cases, the cooling power lost at the primary heat exchanger was 70-80% of the amount of additional heat applied to the secondary heater on the pulse tube. From the perspective of thermodynamic efficiency, this is not an efficient way to achieve 2 stages of cooling, and a well-designed 2-stage pulse tube would require less input power than a 2-stage cooler made this way. However, for gas liquefaction, these results do show that the efficiency of a liquefier will be improved by precooling the gas stream along the pulse tube, compared with a liquefier which simply cools the gas at the cold tip. This is because the total cooling capacity does increase, though with some of that cooling coming at a higher temperature. This result is similar to the NIST results for regenerator precooling [1, 2], though no quantitative comparison can easily be made between the two precooling techniques, since the measurements were made in different ways. This efficiency increase also applies to precooling electrical leads, microwave waveguides, structural mounts, and other instrument parasitic heat loads

CONCLUSIONS

Lockheed Martin Space Systems Company has developed a low mass pulse tube cryocooler with high cooling capacity and high power density, applicable to long-life cryogenic storage and cooling for large cold optical structures. The cooler is capable of providing 20 W of cooling at 70 K with a mass of just 7 kg. Testing of a secondary heater mounted to the pulse tube was conducted, and although this technique does not appear to be an efficient way to make a 2-stage cooler, it does show that one can precool a gas stream by flowing it along the pulse tube and achieve higher liquefaction efficiency compared with simply liquefying the gas at the cold tip.

ACKNOWLEDGEMENTS

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REFERENCES

1. Radebaugh, R, Marquardt, E.D., Gary, J. and O'Gallagher, A., "Regenerator Behavior with Heat Input or Removal at Intermediate Temperatures," in *Cryocoolers* 11, edited by R. Ross, Jr., Kluwer Academic/Plenum Publishers, New York, 2001, pp 409-418.
2. Marquardt, E.D., Radebaugh, R. and Peskin, A.P., "Vapor Precooling in a Pulse Tube Liquefier," in Cryocoolers 11, edited by R. Ross, Jr., Kluwer Academic/Plenum Publishers, New York, 2001, pp 803-807.
3. Wang, C., "Extracting Cooling from the Pulse Tube and Regenerator in a 4 K Pulse Tube Cryocooler," in Cryocoolers 15, edited by R. Ross, Jr., Kluwer Academic/Plenum Publishers, New York, 2005, pp 177-184.