

An ultra-low vibration cryocooling kit based on a miniature Rotary Compressor

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ABSTRACT

The problem of active cooling for photo detectors in “nano-satellites” becomes more important because the majority of space missions target Earth observation, and passive cooling does not provide the required temperatures to achieve the desired Signal to Noise Ratio (SNR) levels. Reciprocating compressors used in cryocoolers cause vibrations. VERT Rotors has developed a miniature Conical Rotary Compressor (CRC) with a 1:12 pressure ratio to enable an active heat management system for small satellites (Rotary Cooling System, or ROCS). The main differentiation of CRC is that it runs with virtually no vibration which is beneficial for operation with image sensors in a small hull. With a high compression ratio ROCS is designed to remove 20W of heat, cool to 120-150K, and run at COP >1 (using less energy for operation than it removes). A prototype of the compressor has been tested, and the ROCS system is undergoing laboratory tests.

THE RATIONALE FOR A LOW-VIBRATION ACTIVE CRYOCOOLER

Heat removal and temperature control has become a highly important issue with CubeSats and small satellite platforms (1m x 1m x 1m - scale). With increasing power budgets on CubeSats, increasing radio power requirement and higher data rates, an efficient heat rejection technology is required. The tasks for such a system include moving tens of watts away from a heat source to radiate at an external face in order to keep radio units and optical lenses cool, or for transferring that heat to another subsystem on orbits where there are long eclipse periods.

An overview of the available heat management options suggests the following:

1. Passive cooling systems with heat sinks have proven to be effective in a range of approximately 258K to 313K for sun synchronous orbits [1]. A more sophisticated passive cooling system PRISMA with ethane circulation between the cold and hot radiators is capable of removing about 4.8W of heat and cooling to below 185K [2].

2. An active system developed by Lockheed Martin demonstrated removal of 0.65W and cooling to 150K. [3]
3. Cryocooling systems based on Stirling engines produce vibrations with two pistons constantly moving in reciprocating motion, and are not a favorable solution for the image sensors.

Removal of tens of watts of heat and cooling to below 180K in a small satellite still remains a challenging task. The decision was made to design such a system that would both enhance the Signal to noise ratio (SNR) in Earth observation in the infrared band, and improve the efficiency of the CPUs. Cryocooling the image sensors becomes a major requirement when Earth observation and remote sensing is estimated to account for 52% of small satellite missions in 2014-2016 [4,5]. In space, excess heat can only be removed from satellites by radiation from black panels. Due to the limited outer surface area of CubeSats, the effectiveness of passive cooling by radiation is limited. An active system would be significantly more effective with the compressor heating the refrigerant through compression. Specifically, the Stefan–Boltzmann law states that while the total energy radiated per unit surface area of a black body is linearly dependent on the surface area of the radiating panels; it depends on

the fourth power of the black body's thermodynamic temperature T:

$$P = A \epsilon \sigma T_{\text{Rad}}^4 \quad (1)$$

where P is the power radiated to space in W, A is the surface area of the radiator in m², ϵ is the emissivity of the black panels, and σ is the Stefan–Boltzmann constant (5.6704×10^{-8} Watt / m²·K⁴).

An active cooling system elevating the temperature of gas through compression and enhancing radiation of heat through black panels would be the most appropriate solution. Using the formula (1) it can be calculated that to achieve the cryocooling temperature of the refrigerant of 116K and to remove 40W into Space a passive system would need a surface area of over 5m². In comparison, for an active system only 1.1 m² radiation surface will be necessary. The difference is that an active system compresses refrigerant (krypton in this particular case) from 1 bar (a) to 12.3 bar (a), with a discharge temperature elevated from 120K to 328K which is very beneficial for black body radiation. Along the condenser the refrigerant temperature will progressively drop, until reaching 116K.

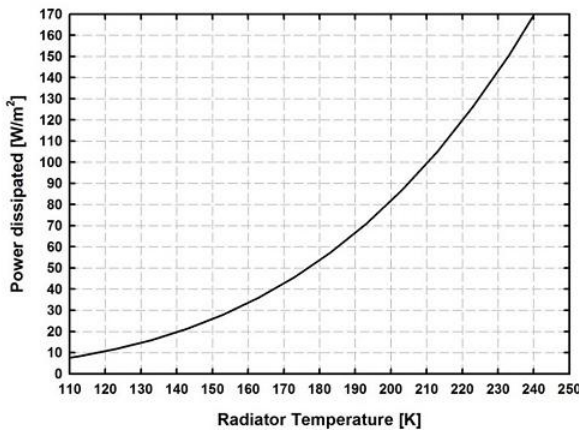


Figure 1. Function of power dissipation W/m² from the Radiator Temperature

Cryocooling System Requirements to a Compressor

This dictates a few key requirements for a compressor that would be appropriate for an active cryocooling system:

- Providing a compression ratio of at least 1:6 to heat the gas.
- Supporting the target cooling temperature below 150K (as low as possible).
- Supporting the removal of 10-20W of waste heat.

- Being very energy-efficient so that COP should be greater than 1 (compression power < cooling power).
- Compact footprint within 100mm x 100mm x 40mm.
- Low mass, below 200g, because of the high cost of delivering the payload to space.
- Most importantly, the compressor should produce as little vibration as possible, because vibration is unfavourable for optics in Earth observation satellites.

The other small compressors that are available are well-suited for certain applications, but for Earth observation missions the level of vibrations must be improved to reduce the impact on image sensors. Existing Stirling-type micro-compressors with reciprocating motion naturally have inherent vibrations. More advanced active techniques, such as the space proven Stirling and Joule–Thomson cryocoolers surpass volume and mass capabilities of CubeSats. Examples of these include the 4.3 kg Oxford cryocooler employed on UARS with cooling capability of 0.8W at 80K [1].

It was concluded that a rotary design would be the most appropriate for a low-vibration and very small compressor. The challenge of the oil-free rotary designs is that they do not provide high compression ratios over 1:1.5 when implemented in very small sizes. For this reason it is typical that piston-type compressors are used in very small applications.

DESIGNING A MINIATURE CONICAL ROTARY COMPRESSOR

Results of the design project

A “nano” rotary conical compressor (codename “MK03”) was designed. The screw length is 40mm, and it fits onto a 100mm x 100mm board. MK03 is a rotary compressor which ensures very low vibration.

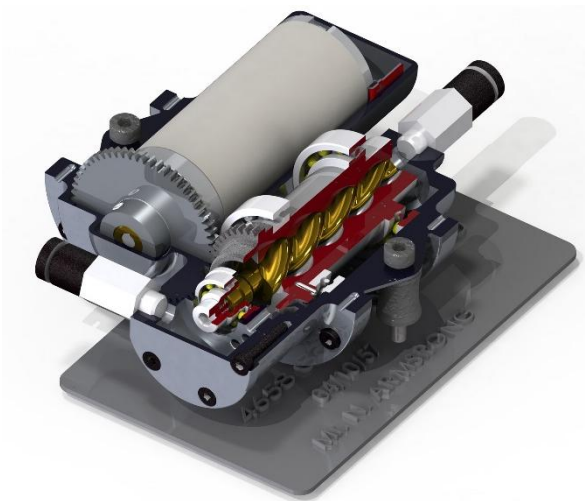


Figure 2: MK03 in comparison with a credit card

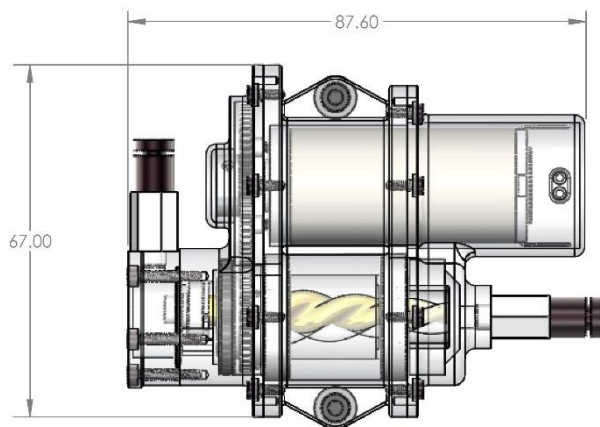


Figure 3: Dimensions of the MK03 fitting onto the 100x100 frame

MK03 is a Conical Rotary Compressor (CRC) which is a novel design consisting of one Inner conical screw rotor revolving inside an Outer conical screw rotor. In comparison, conventional twin-screw compressors consist of three elements, two screws revolving inside the housing.

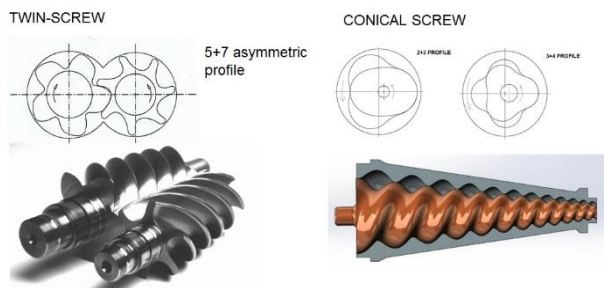


Figure 4. Comparison of twin-screw and conical screw profiles

Principle of operation of Conical Rotary Compressor

In the conical compressor, the compression chamber is formed by the volume trapped in between the Inner and the Outer rotors. The Inner rotor axis is angularly offset from the Outer rotor axis and revolves inside it as the rotor itself rotates.

In operation, a compressible gas is drawn into the assembly at the large end of the cone. The chamber coloured in blue is in the position that the flow will be cut off from the suction port [6].

As the inner rotor and outer rotor rotate, each of the closed chambers reduces in size as it travels from the large end to the small end of the cone, thereby compressing the gas. High-pressure gas discharges from the assembly at the small end of the cone.

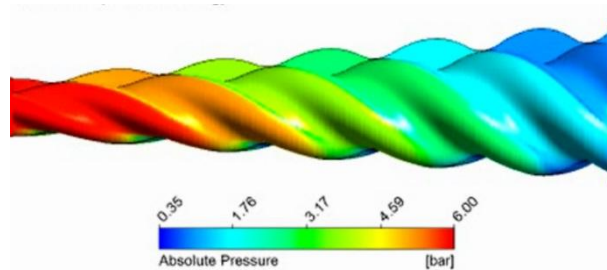


Figure 5. Gradual increase in pressure in CRC

DESIGN OF AN ACTIVE CRYOCOOLING CYCLE

We started with a question: could we design a cycle where (a) more cooling power would be removed from CubeSat than compression power, and (b) the final cooling temperature will be lower than 150K (-123 °C)?

First we analysed the Linde cycle. It confirmed that using the mixture of Nitrogen/Hydrocarbons with a radiator temperature of 150K, a single-compression cryogenic cooler is thermodynamically feasible. However to produce 20W of cooling power, 99.5 l/min of a nitrogen-hydrocarbons mixture were needed. The after-cooler should exchange a thermal power of: $Q_{aftercooler} = \dot{m}_{refrigerant} * \Delta h_{aftercooler} = 0.430kW$. This requirement was well above the feasible energy budget of a small satellite, and the idea of using Linde cycle for this application was dropped.

Because of the limited CubeSat power budget for compression, and also because of the low efficiency of Linde cycle, we can conclude that a Carnot-based cycle is more appropriate for this application. A key

requirement to this cycle is that $COP > 1$ so that the compression power is less than the evaporation power:

$$COP = \frac{Q_{ev}}{Q_{comp}} \geq 1 \quad (2)$$

where Q_{ev} is evaporator power, Q_{comp} is compressor power.

We analysed gases having most gradual slope smallest slope of the saturation curve and condensing at $T_{cond} = -120^\circ\text{C}$ and designed a gas mixture based on krypton. Krypton has an isentropic exponent of 1.67 and heats up very well in compression, while adding other gases allowed the triple point to be brought down and the feasible evaporation temperature lowered. A Carnot-like refrigeration cycle has been designed based on a 1:12 compression ratio, with evaporation temperature of 120K. With compressor power of 16W (based on 75% efficiency) and 20W or waste heat removal this cycle achieved $COP > 1$.

The schematic of such a cryocooling system is outlined on the drawing below:

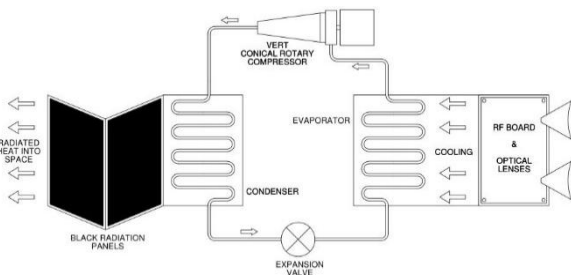


Figure 6. Cryocooling system based on the MK03 Conical Rotary Compressor

PRODUCTION AND EXPERIMENTAL VALIDATION

Next, the conical compressor's ability to deliver the 1:12 pressure ratio had to be validated.

First, a bigger prototype "MK3" was built, with 167 mm-long conical rotors. This unit provided air compression ratio of 1:22 in a single stage in oil-free operation, at 830 r/min.

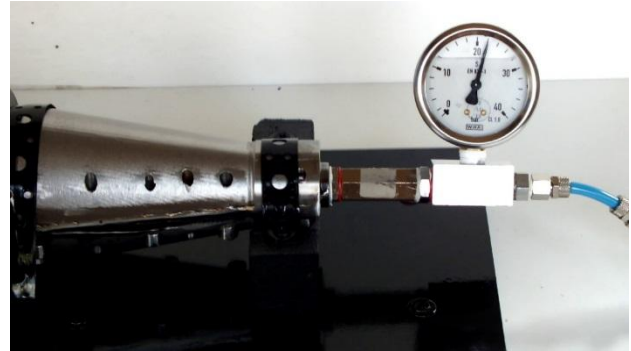


Figure 7. MK3 compressor test showing 22 bar (g) compression in a single stage

Based on the ground work that had been done with larger machines, a working prototype "MK03" with 40mm-long conical rotors was built. During tests this machine compressed air to 12 bar (g) in a single stage.

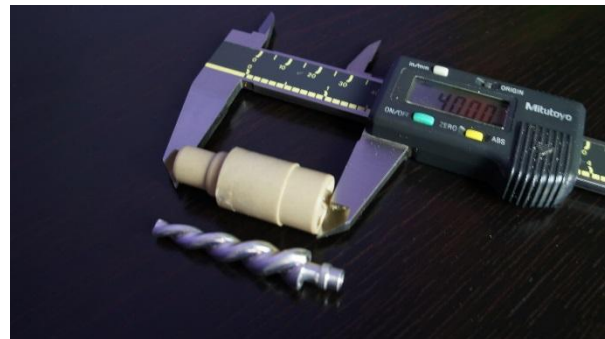


Figure 8. 40mm Inner and Outer rotors of MK03

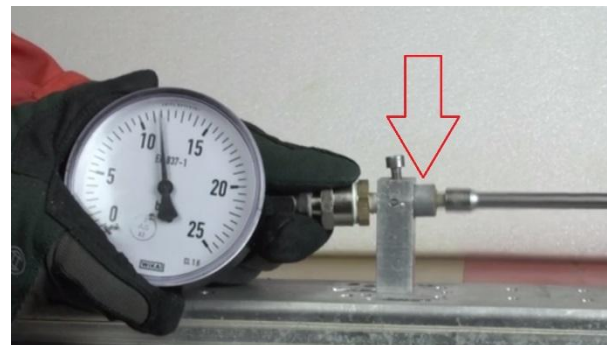


Figure 9. MK03 test results, 12 bar (g)

After that we designed and built a full-scale version of MK03 hermetic assembly for compressing and containing gas under high pressure.



Figure 10. Hermetic assembly cooler based on the MK03 compressor

At the time of publication the authors were integrating the hermetic assembly of the MK03 compressor into a cryocooling kit and testing it. The target end result is to have a fully operational 1:1 experimental model mounted onto a 100mm x 100mm PBC, suitable for installing into a CubeSat.

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