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A miniature Rotary Compressor with a 1:10 compression ratio

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Abstract. Micro compressors have applications in medical devices, robotics and “nano-satellites”. 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 SNR levels. Reciprocating compressors used in cryocoolers cause vibrations. VERT Rotors has built an ultralow-vibration rotary compressor with 40mm-long screws, and our prototype delivered 1:10 compression ratio. This “nano” compressor is a non-conventional conical type consisting of an Inner conical screw rotor revolving inside an Outer screw rotor.

1. The need to develop a very small rotary compressor with high compression ratio

Heat removal and temperature control has become a highly important issue with “nano-satellites” (100x100x100mm – scale, so-called “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 active 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 (for example keeping the battery at operational temperature without using a wasteful heater).

Thermal control of CubeSats is usually passive with heat sinks and optical tape on the outer structure keeping the structure, with the exception of the solar panels, in a range of approximately 258 K to 313 K for sun synchronous orbits [1]. This is not sufficient for cooling down the photo detectors to 180-200K, which becomes a major requirement when Earth observation and remote sensing is estimated to account for 52% of small satellite missions in 2014-2016 [2,3]. The signal-to-noise ratio (SNR) of photo detectors is affected by temperature because dark noise from thermal excitation increases with temperature, as it follows the temperature dependence of the concentration of electrons in the conduction band, shown in the equation below:

$$n_0 = k_3 T^{-1.5} e^{-(k_4/T)} \quad (1)$$

where n_0 is the concentration of electrons in the conduction band, T is the temperature, and k_3 and k_4 are constants that depend on technology. Based on this equation, in order to obtain an SNR of 100 a temperature of about 187K is required [4]. While this is just a particular example, it is generally true that, in order to achieve reasonable SNR, cooling down of the sensor becomes a necessity.

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 gas 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 :



$$P = A \varepsilon \sigma T_{\text{Rad}}^4 \quad (2)$$

where P is the power radiated to space in W, A is the surface area of the radiator in m^2 , ε is the emissivity of the black panels, and σ is the Stefan–Boltzmann constant ($5.6704 \times 10^{-8} \text{ Watt} / \text{m}^2 \cdot \text{K}^4$) [5].

An active cooling system elevating the temperature of gas through compression and enhancing radiation of heat through black panels would be the most feasible solution. A few key requirements of a compressor in an active system are:

- To provide a compression ratio of at least 1:3 to heat the gas.
- To support removal of 10-20W of heat.
- Very small footprint within 100mm x 100mm x 40mm.
- Low mass, below 100g, 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 reciprocating-type micro-compressors naturally have inherent vibrations. One such compressor built by Lockheed Martin has mass of 190g; the net cooling capacity of this machine is 650mW at 150K, corresponding to specific power of 15.4 W/W [6]. 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 80 K [1].

It was concluded that a rotary design would be the most appropriate for a low-vibration 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.

2. Designing a “nano” conical rotary compressor

2.1. Results of the design project

A nano rotary conical compressor with a 1:4 volume ratio (codename “MK03”) was designed. The screw length is 40mm, and it fits onto a 100mm x 100mm PCB. MK03 is a rotary compressor which ensures very low vibration.

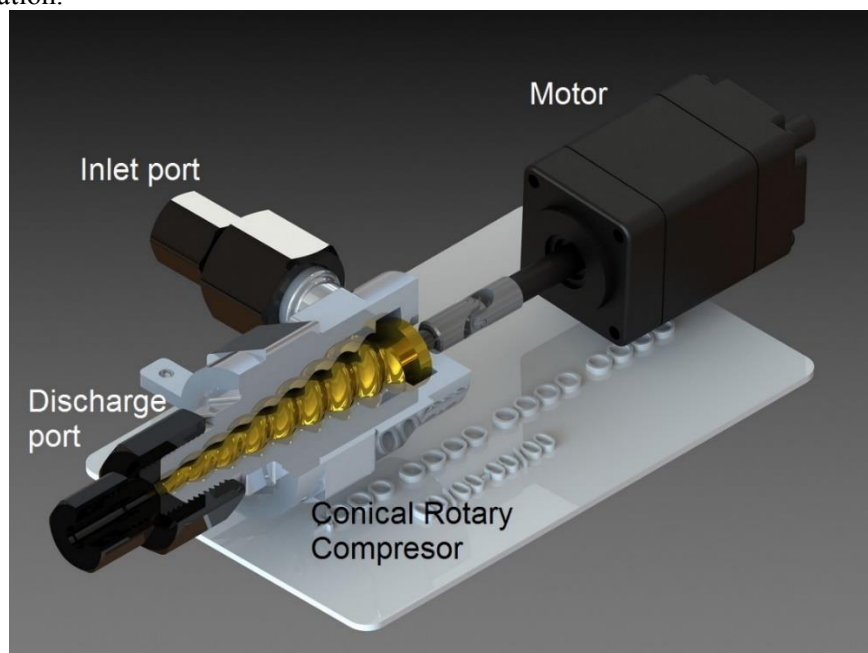


Figure 1. MK03 in comparison with a credit card

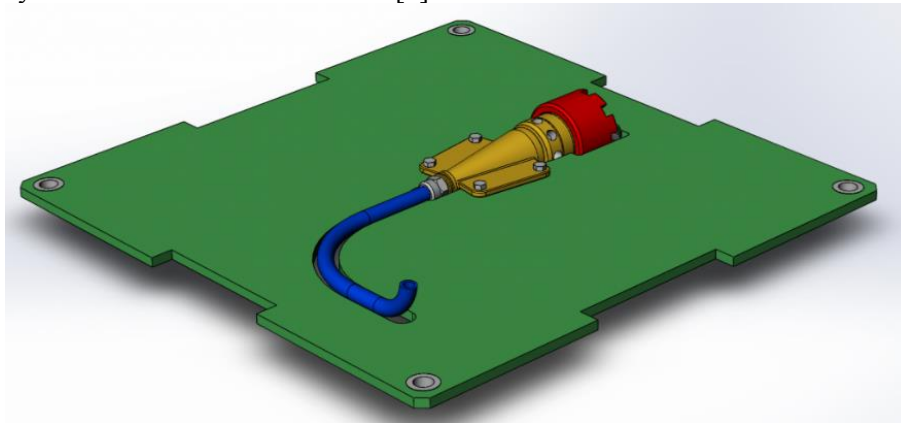
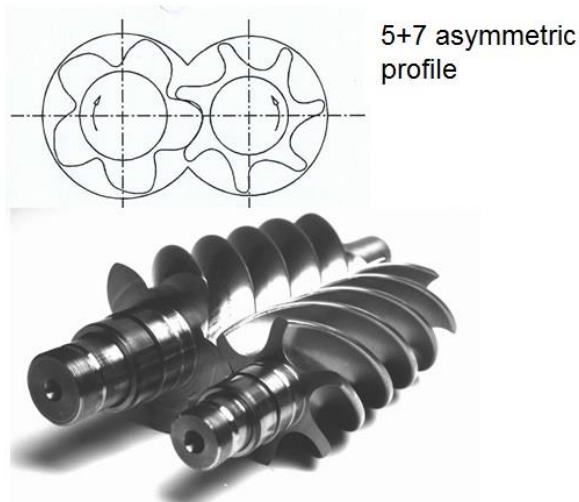


Figure 2. Nano CRC mounted on a 100mm x 100 mm board

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.

TWIN-SCREW



CONICAL SCREW

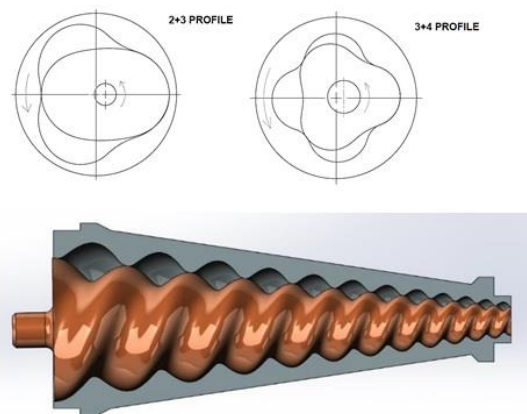


Figure 3. Comparison of twin-screw and conical screw profiles

To create the MK03, a mathematical formula and algorithm for generating mating conical screw rotors was developed. 3D CAD software that outputs screw profiles in 3D format, suitable for further CAD-CAM processing and machining was written. After several years of optimisation, the generation of screw profiles was fully automated and the process duration has been reduced to a few hours.

2.2. Operation of Conical Rotary 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 [7].

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.

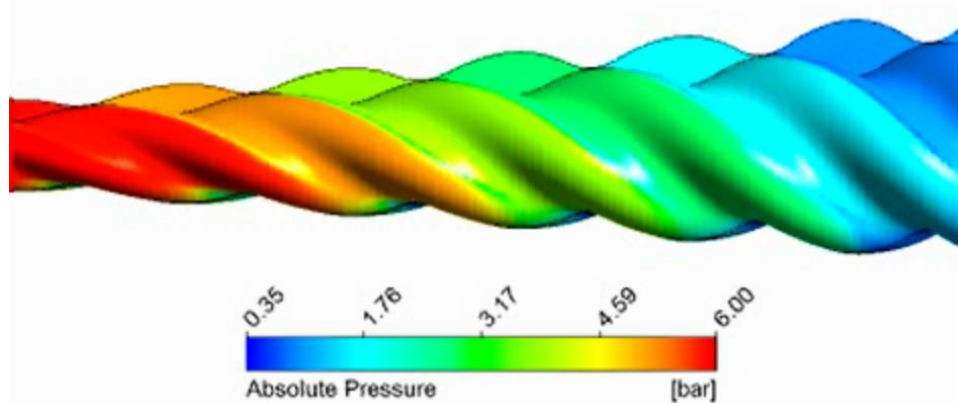


Figure 4. Gradual increase in pressure in CRC

2.3 Comparison of conical screw and twin screw designs

Perhaps the most important difference is that, within the CRC, the Inner rotor makes a rolling motion inside the Outer rotor thereby using the full volume inside the Outer rotors, therefore the CRC does not have a “blowhole”, which is a typical feature of twin-screw compressors [8]. Leakage flow is the main cause of reduced efficiency in twin-screw compressors [9]. The “Blowhole” is a gap where two screws and a housing meet, and compressed gas from the high-pressure area leaks back to the low-pressure area. To overcome this problem, oil-free twin-screw compressors run at high rotational speeds. The CRC, not having a “blowhole”, can potentially run at a higher efficiency, but it can be impaired by higher friction. To realise its potential the CRC should be made from low friction materials.

Secondly, due to the small discharge area and the gradual reduction of the swept volume, the internal pressure ratio of the CRC is “self-adjusting” to the external pressures, i.e. the required pressures of the system in which the compressor operates, which allows the compressor to work to the optimal discharge pressures. Therefore, the CRC does not suffer from over-compression or under-compression [7].

The efficiency of a positive displacement compressor (piston, scroll, screw, vane or any other) greatly depends on the capability of the machine to adjust the internal pressure ratio to the “external”, or system, pressure ratio.

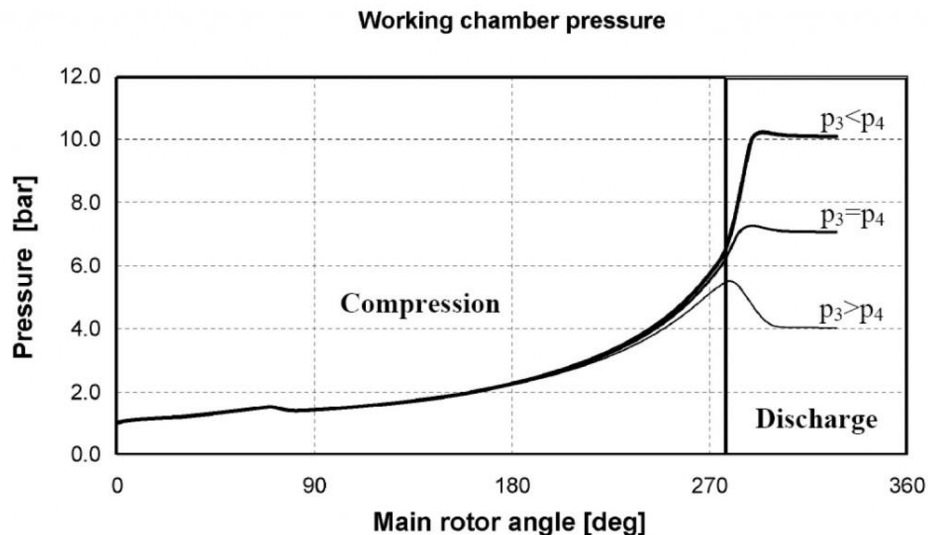


Figure 5. Pressure angle diagram of twin-screw compressors

If the “external”, or system, pressure is higher than the internally-achieved pressure ($p_3 < p_4$), this condition is called under-compression and requires additional work to push the fluid out of the compressor, by which process its pressure will increase to the external discharge pressure. If the external pressure is lower than the internally achieved pressure ($p_3 > p_4$), this condition is called over-compression and it indicates that unnecessary work has been used in the compressor to compress the

If the volume ratio $[V_i]$ is constant, the pressure increase during the compression process (called internal compression) will be more or less constant and independent of the external, or system, pressure ratio. It can be calculated as:

$$p_3 = p_2 V_i^\gamma \quad (3)$$

where γ is the isentropic exponent of gas.

As shown in Figure 5, if the internal pressure p_3 matches the external pressure p_4 the compression process is optimal and no additional losses are generated.

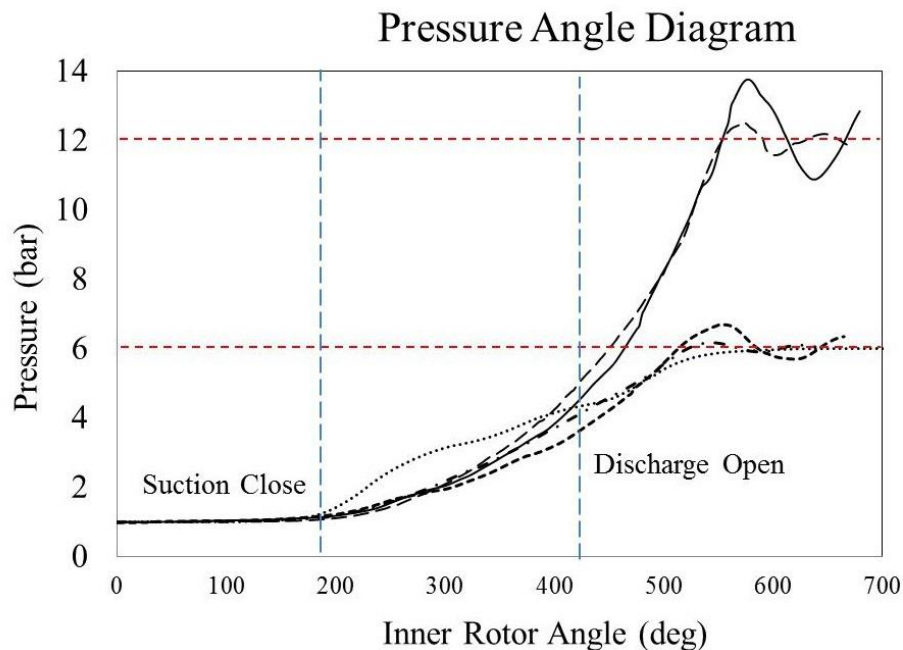


Figure 6. Pressure angle diagram of CRC

Figure 6 shows the calculated indicator diagram for a CRC. As can be seen in the diagram, this machine in all calculated cases achieves matching internal and external (system) pressures irrespective of speed or pressure ratio. It can be seen, therefore, that the CRC has a “self-adjusting” internal pressure ratio.

The working chamber which is connected to the discharge port has a very long slender shape, while the area through which it connects to the discharge pipe is small. This is a favourable feature, as it causes the compressor’s “internal” pressure to gradually match the “external”, or system, pressure at the rate at which this happens during internal compression.

In a typical twin-screw compressor this is different since, in these machines, the discharge port normally opens much wider, causing much faster equalisation of internal and external pressures which, although reducing the dynamic flow losses, still increases the required power.

The relatively small size of the discharge port in a CRC and its gradual change additionally helps to reduce pressure oscillations in the discharge port. Therefore, as seen in Figure 6, pressure pulsations exist but are not large at any pressure. In a typical twin screw compressor, these oscillations will be very small when the internal and external discharge pressures are matching but could be excessive if these are very different.

Thirdly, an axial discharge arrangement also improves energy-efficiency. As the report by the Centre for Positive Displacement Compressors concludes: “The conical design of the compressor and the axial discharge arrangement ... is a unique advantage of this compressor.”[7] In a typical twin-screw compressor, the suction and discharge ports are tangential to the screw axis. This creates additional resistance and leads to energy losses.

2.4 The most compact rotary machine compressing air at 11 bar(g) in a single stage

The experimental studies carried out by our team in Edinburgh showed that MK03 was compressing air at 11 bar(g) in a single stage at 6,000 r/min shaft speed. This confirms that even very small CRCs can provide high compression ratios at standard shaft speeds thanks to progressive compression of gas inside the Outer rotor while it travels from the suction end to the discharge end. Effectively the CRC is the smallest rotary screw design on the market today capable of providing such compression ratio. Today's screw compressors are big industrial machines with a lower limit of displacement standing at approximately 20m³/h at 3000 r/min [10], but typically at 80m³/h [11].

In the oil-injected applications MK03 can be used to compress air to 8-10 bar(g), while in the oil-free operation the reasonable discharge pressures should be limited to 3 bar (g) to avoid overheating.

2.5 Thermodynamic model

To adjust the performance of the CRC, a numerical model for cooling a CubeSat with RF boards generating 20-30W of heat (80W of heat in total including contribution of the solar radiation and the compressor itself) was developed.

CubeSat is cooled from any temperature to which it was heated by the RF panels and optics and converge and stabilise at the equilibrium temperature.

2.5.1. Assumptions

Refrigerant gas: Helium

Refrigerant Flow Rate: Flow = 3 l/min

Compression ratio 1:3

The size of the black radiation panels for CubeSat is 0.12m² (two 300mm x 100mm x 100 mm "cards" on the shadow side of a CubeSat).

Emissivity of black panels $\varepsilon = 0.96$

2.5.2. *The model.* The gas discharged from the Compressor needs to be heated to the temperature that will be sufficient to radiate 80W of heat through the black panels of the Condenser. The required temperature is derived according to the Stefan-Boltzmann law, formula (2) above.

The required flow of the coolant = 8.923×10^{-6} kg/s

Temperature of gas leaving the compressor: $T_1 = 368\text{K}$

Energy that is radiated by the black panels from the heated refrigerant is calculated using the formula (2), in this case it is 119.4W

After the gas has left the "black panel" condenser, its temperature drops to $T_2 = 239\text{K}$

The pressure in the condenser decreases to $p_2 = 1.9$ bar (a)

When the gas passes the Expansion valve, its pressure drops to 1 bar (a).

In the Evaporator the gas expands and its temperature goes down to $T_3 = 183\text{K}$

The refrigerant cools down the payload. Its temperature rises to $T_0 = 237\text{K}$, which will be the equilibrium temperature of the CubeSat.

3. Production and experimental validation

Several working prototypes of CRC were built to validate the concept. A prototype "MK3" unit with 167 mm-long conical rotors with a 1:10 volume ratio provided air compression ratio of 1:22 in a single stage in oil-free operation, at 830 r/min. Another machine codenamed "MK7" with 220mm-long conical rotors with a 1:2 volume ratio was extensively tested for oil-injected air compression over a period of 3 months. It was producing 130 l/min (7.8 m³/h) at 8 bar (g) load at 52.5Hz. MK7 has a remarkably low noise level even without an acoustic enclosure, allowing two people to have a conversation while standing next to the working compressor. These prototypes validated the concept of conical rotors.

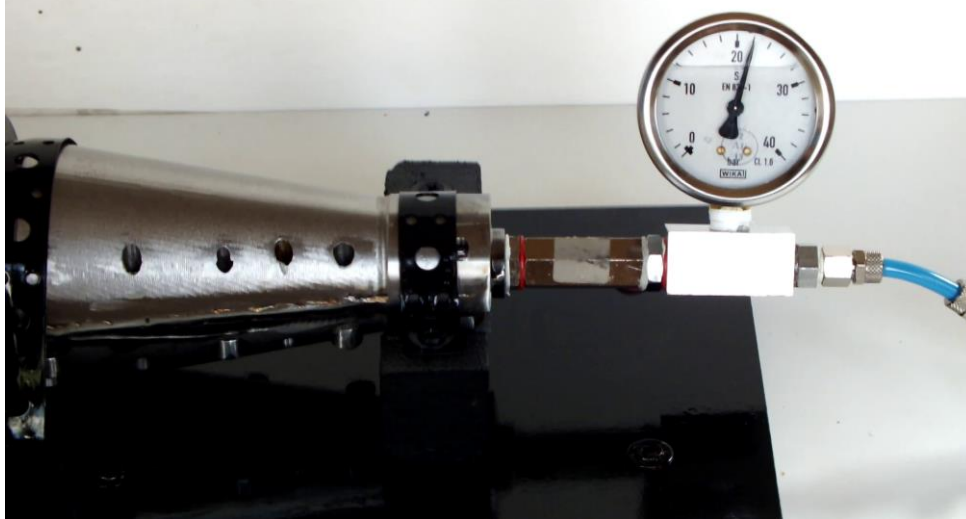


Figure 7. MK3 machine test showing 22 bar(g) in a single stage

Based on the ground work that had been done with larger machines, a working prototype “MK03” with 40mm-long conical rotors with a 1:4 volume ratio was built and tested. This was produced by rapid prototyping, and during initial tests this machine compressed air to 10 bar (g) in a single stage.



Figure 8. MK03 prototype

Test results demonstrate that CRC is the smallest operational rotary compressor that runs at the 1:10 pressure ratio.

4. Next steps: Developing a nano-cryocooling kit

For the next step, the authors aim to build and test the ultra-compact and low-vibration cooling kit based on the MK03 compressor. The end result will be a fully operational 1:1 experimental model mounted onto a 100mm x 100mm PBC, suitable for installing into a CubeSat (see Figure 9 below).

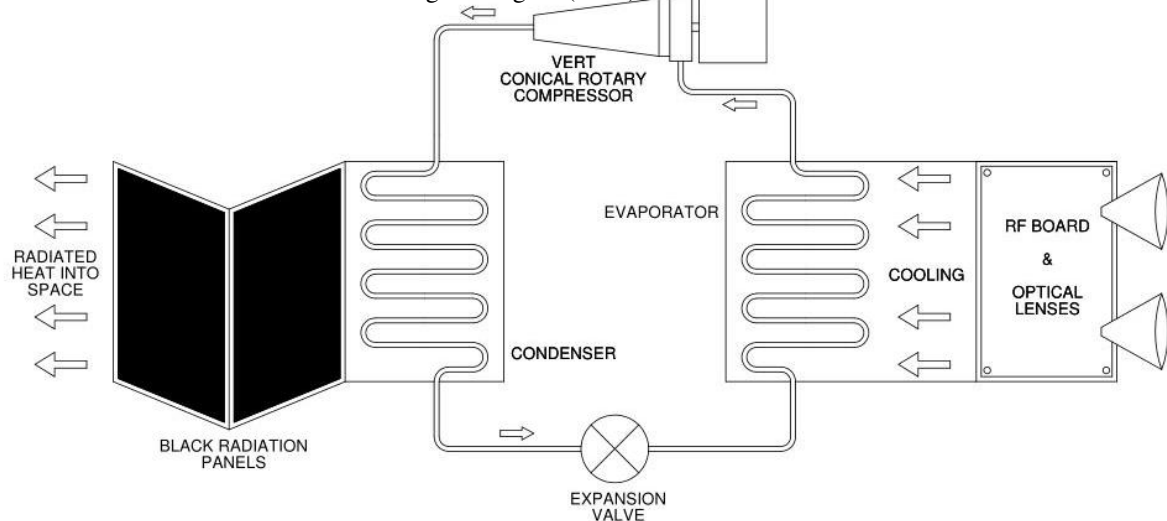


Figure 9. Diagram of the cooler based on the MK03 compressor

References

- [1] A survey and assessment of the capabilities of Cubesats for Earth observation, D.Selva, D.Krejci, *Acta Astronautica* 74 (2012) 50-68
- [2] 2014 Nano/Microsatellite Market Assessment, SpaceWorks Enterprises Inc.
- [3] Small Satellite Missions, National Aeronautic and Space Administration, www.nasa.gov
- [4] G.H. Rieke, *Detection of Light: From the Ultraviolet to the Submillimeter*, Cambridge University Press, Cambridge, UK, 2003.
- [5] Stefan-Boltzmann Law, Encyclopaedia Britannica, www.brittanica.com
- [6] Microcryocooler for Tactical and Space Applications. J.R. Olson , P. Champagne, E. Roth, T. Nast, E. Saito, V. Loung, A.C. Kenton and C.L. Dobbins. AIP Conference Proceedings, 2014.
- [7] Kovacevic, A., Rane, S. (2103), CFD Analysis of VERT Labs Helical Rotary Compressor HRC-1, City University London, UK
- [8] The Design and Application of Rotary Twin-Shaft Compressors in the Oil & Gas Process Industry, EurIng Ian M. Arbon CEng, FIMechE, Mechanical Engineering Publications, 1994.
- [9] Buckney, D., Kovacevic, A., Stosic, N.,(2011), Consideration of clearances in the design of screw compressor rotors, 7th International Conference on Compressors and their Systems, City University London
- [10] <http://www.atlascopco.co.uk>
- [11] Kevin Glass, Compressors: Small screw drivers, Bitzer UK <http://www.acr-news.com/compressors-small-screw-drivers>