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80 K vibration-free cooler for potential future Earth observation missions

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Abstract. A solution for a “vibration-free” Joule-Thomson cooler using a sorption compressor is presented to answer the needs of potential future Earth observation IR missions with low micro-vibration levels requirements from the European Space Agency. The adopted solution includes a closed cycle JT cooler, using nitrogen as working fluid with an expected cooling power of 1.5 W@80 K and the fluid circulation is achieved by cycles of adsorption/desorption using metal organic framework sorbent materials.

The working principle and chosen parameters of the 80 K vibration-free cooler are shown based on the various stringent requirements (temperature range, performance, consumption etc.) The characterization and validation of some components was already carried out: preliminary results are presented.

1. Introduction

The space cryogenics sector has a large number of applications that lead to several stringent requirements (temperature range, micro-vibration, lifetime, consumption) that can be met by different solutions like Joule-Thomson (JT) or Stirling/Pulse Tube coolers, mechanical or sorption compressors (SC) etc.

Nowadays, the current development of coolers to meet Earth observation missions requirements are capable of providing significant cooling power at an operational temperature of 80 K. But, they often rely on mechanisms involving moving parts, that still induce micro-vibrations. Even with active micro-vibration cancellation, careful screening and manufacturing of the cooler parts, unsolicited vibrations still remain.

With the development of magnetic bearing reaction wheels and microthrusters, the classical Earth observation cryocoolers (Pulse Tube, Stirling) will become the main source of vibration. It is then necessary to develop alternative cooling solutions or adapt current technologies. The Darwin development studies covered 15 K and 4 K class coolers [1], but a need also exists in the 40 K to 80 K range for IR detection.



To achieve this objective, ESA launched a technical research program to develop new, or to adapt, cooling technologies in this temperature range without mechanical disturbances and continuous cooling [2].

In this project, a Portuguese consortium (LIBPhys-UNL and Active Space Technologies) is currently working together to develop a 80 K nitrogen JT cooler. The fluid circulation is guaranteed through a sorption compressor, that needs a minimum of four sorption beds [1], each one filled with a sorbent material chosen specifically for the purpose.

The use of cooling systems based on thermal compressors and JT cooling effect, is a very attractive technology that provides cooling with, theoretically, no induced micro-vibrations. Moreover, this technology provides excellent flexibility for its integration in spacecraft.

According to ESA's requirements, the 80 K vibration-free cooler has to reject its heat of compression through a radiator. The maximum surface of this radiator is 1.5 m^2 , that has an heat-sink temperature of 90 K. The targeted operational conditions of the cooler is to provide uninterruptedly cooling with a heat lift ranging from 1.0 W to 1.5 W @ 80 K.

The 80 K vibration-free cooler consists of two main sub-systems, the Joule-Thomson stage and the sorption compressor described next.

2. 80 K JT circuit

A basic JT cooler employs a Linde-Hampson cycle, which includes a recuperative counter-flow heat exchanger (CFHX), a JT restriction and an evaporator (liquid reservoir), which is schematically shown in Figure 1a. The JT effect is a well known thermodynamic behaviour of real gases: upon certain conditions one can achieve a temperature drop of a given fluid, by forcing an expansion of the fluid through a valve or an orifice (isenthalpic process). The process followed in our system is represented on a pressure-enthalpy (P-h) diagram, as shown in Figure 1b.

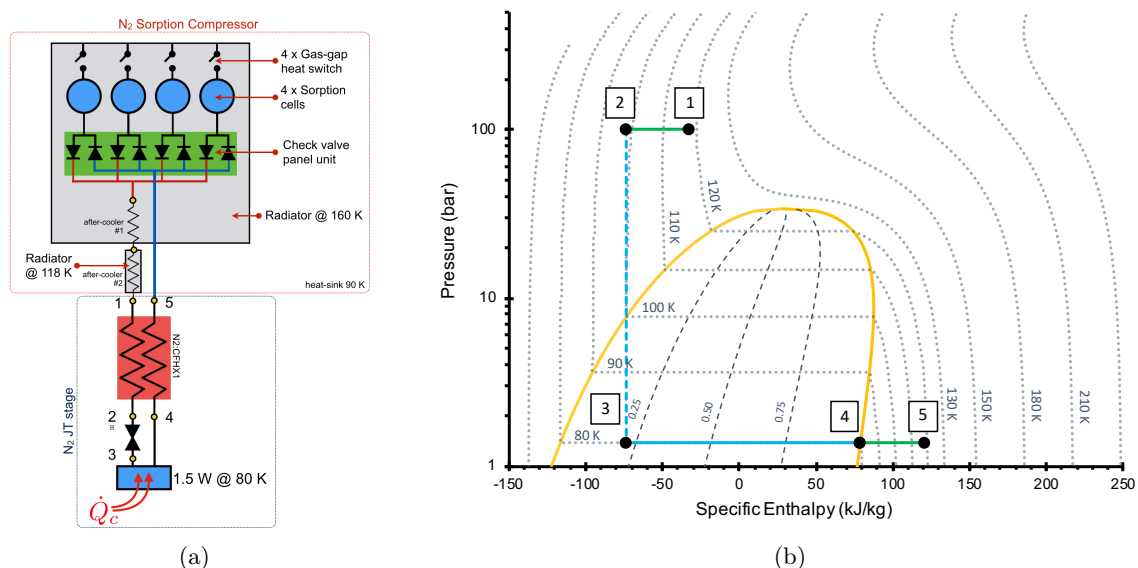


Figure 1: a) Schematic of the proposed vibration-free cooler. b) Linde-Hampson cycle on a P-h plane, with nitrogen operating from a warm end temperature of 120 K and 40 bar.

A previously pre-cooled high pressure gas stream enters the CFHX (state point 1) and is further pre-cooled along the CFHX, by exchanging heat with the cooled returning gas (state points 4 to 5). After this pre-cooling process (state point 2), an isenthalpic expansion occurs resulting in a temperature drop, the so called JT cooling effect, where part of it liquefies (state

point 3). This liquid is vaporized by receiving heat load coming from the device to be maintained at low temperature (state point 3 to 4). The available heat lift of the cooler $\dot{Q}_c$ is expressed as,

$$\dot{Q}_c = \dot{m}(h_4 - h_3) = \dot{m}(h_5 - h_1) \quad (1)$$

where, $\dot{m}$ is the mass-flow rate, h the specific enthalpy, the subscripts corresponding to the state points in Figure 1.

In the 80 K temperature range, the pure fluids that exists under saturation conditions are oxygen, nitrogen and carbon monoxide. Their thermo-physical properties can be found in Table 1. Oxygen presents the lowest saturation pressure that makes it not adequate to be used in the SC since adsorption is promoted by higher pressures. Its lower triple-point, allowing a wider temperature range, and its higher saturation pressure, makes nitrogen more attractive than carbon monoxide for the development of the cooler.

Table 1: Saturation properties of oxygen, nitrogen and carbon monoxide, possible candidates for the development of the 80 K cooler.

	Oxygen	Nitrogen	Carbon monoxide
Triple-point / K	54.36	63.15	67.95
$P_{\text{sat}}(80 \text{ K})$ / bar	0.30	1.38	0.84

A thermodynamic analysis of the nitrogen JT cold stage, starts by assuming: nitrogen is pure (no mixtures); zero pressure drop along both sides of the CFHX; perfect CFHX, that leads to $T_1 = T_5$; and, the returning cold stream gas at state point 4 is always a saturated vapour.

The benefit in terms of extracted heat $\dot{Q}_c$ at low temperature per unit of supplied work $\dot{W}$, is given by the coefficient of performance (COP). Applying the first and second laws of thermodynamics to the system (CFHX+JT restriction), the COP has the following relation,

$$\text{COP} = \frac{\dot{Q}_c}{\dot{W}} = \frac{h_5 - h_1}{T_1(s_5 - s_1) - (h_5 - h_1)} \quad (2)$$

where s is the specific entropy.

Eqs. (1) and (2) are useful parameters for a preliminary optimization of the JT cold state, namely, the high pressure and the warm end temperature (inlet temperature of the CFHX).

In Figure 2, the COP (left side) and the mass flow rate (right side) are shown as a function of inlet pressure for different warm end temperatures and for constant heat lift of 1.5 W@80 K. As expected, as the warm temperature decreases, the performance of the cold stage increases and then the required mass flow rate decreases as well. Moreover, it is interesting to note that for temperatures below the critical temperature ($\approx 127 \text{ K}$), the COP is almost pressure independent. In this region, where the fluid is in the compressible liquid state, the isotherms are nearly vertical. That leads to a liquid fraction pressure independent, and, as well as the heat lift. Moreover, this liquid fraction being quite high turns this region very attractive.

The optimal operating point of a complete cooling chain has to consider the many individual parameters, such as mass flow rate, pressure, warm end temperature, radiator surface and the COP of the sorption compressor (not covered in this article). Varying these numerous parameters it was found configurations where it is viable to add after the 160 K after-cooler a second one at 120 K (Figure 1a), its cooling using only a small fraction of the radiator's surface (close to 0.38 m^2). The remaining surface is used at 160 K interface. The parameters corresponding to the chosen configuration are shown in Table 2 and the resulted cycle in Figure 1b.

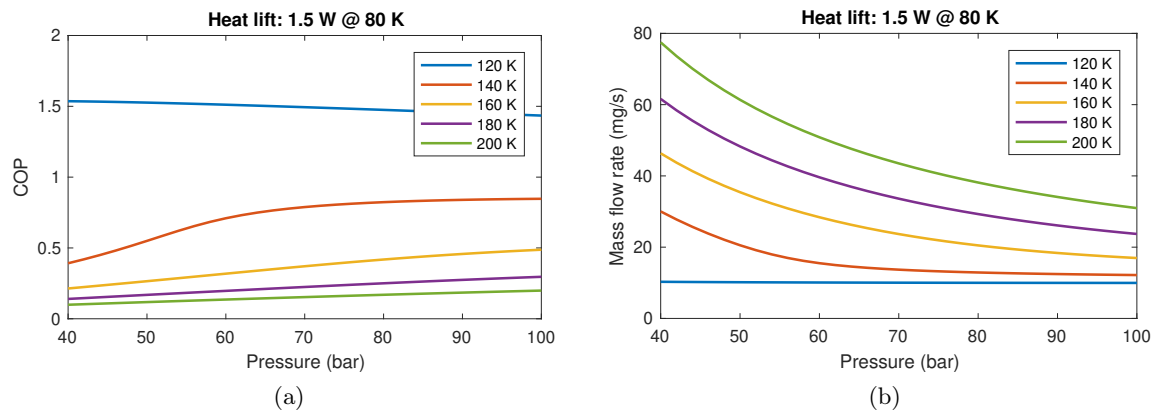


Figure 2: a) Nitrogen JT cold stage COP as function of high pressure for different warm end temperatures. b) Required mass flow to obtain the target heat lift of 1.5 W as function of high pressure for different warm end temperatures.

Table 2: Operating parameters of the nitrogen JT cold stage.

fluid	Heat Lift	Mass Flow Rate	Liquid Fraction	High/Low Pressure	Warm end temperature	After-cooler Radiator area
nitrogen	1.5 W@80 K	10.8 mg s ⁻¹	76.5%	40 bar/1.38 bar	118 K	0.38 m ²

3. Sorption Compressor

3.1. Working Principle

The SC is a vital part of this system, being responsible for the fluid's circulation. It is based on the principle that a certain amount of gas can be reversely desorbed and adsorbed, with a density much higher than of its gaseous phase, by certain solids as, for instance, activated charcoals and metal-organic framework (MOF).

By nature, a SC is an intermittent system, in which, the sorbent bed adsorbs and desorbs the gas. Using four sorbent cells, each one connected to a pair of (passive) forward-reverse check-valves (fig. 1a), and working in quadrature, are able to provide a nearly continuous flow to the JT cold stage to achieve a continuous cooling.

The sorbent cycle of one cell in Figure 3, depicts the amount of gas in the cell during the four distinct phases.

Phase A "Heating": The cell is being heated up with both check valves closed. So, operating at constant quantity. The sorbent's temperature increases, while the adsorbed gas is being released and its pressure increased up to the inlet pressure needed for the JT stage (40 bar in this case).

Phase B "Releasing": At state 2, when the inlet pressure is achieved, the high pressure check valve opens and a gas flow is released to the JT stage. By controlling its temperature increase, the cell provides a constant gas flow into the JT stage while keeping constant the inlet pressure. During this phase, a gas quantity Δn was released from the cell and fed the JT stage.

Phase C "Cooling": When maintaining the pressure and the flow constant becomes impossible (Point 3), the cell starts to cool, the pressure decreases, while passively closing the check valve. The cell is operating at constant quantity.

Phase D "Adsorbing": When the pressure decreases down to the outlet pressure ($P < 1.38$ bar), the low pressure check valve opens and the cell starts to adsorb the gas exiting the CFHX. Adjusting its temperature decreasing rate, the cell adsorbs at the same rate that is flowing

of the JT stage. Doing so, the outlet pressure is constant, maintaining the evaporator at constant temperature. When the adsorbent is no longer able to adsorb at this rate (point 1) the compression cycle is complete and ready to be recycled again.

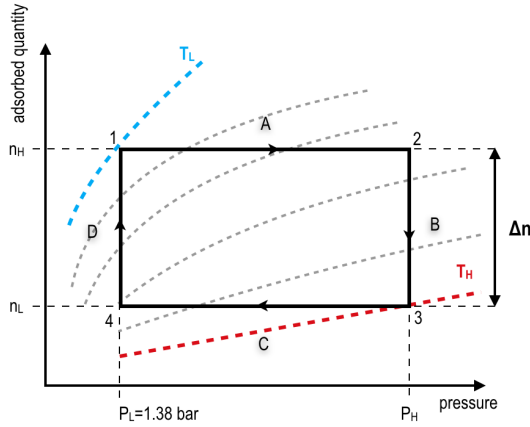


Figure 3: Schematic of one sorption cycle. Adsorbed quantity as function of pressure. Dashed lines are isotherms. The different states/phases are explained in the text.

In this project, the available heat sink of the compressor is rather limited (1.5 m^2 radiator, radiating to 90 K). This implies that, the operation of the compressor has to be performed with low heat load and a relatively high adsorbing temperature T_L at state 1 (fig. 3); for our system, T_L around 160 K and 180 K was found to be a good compromise. On the other side, from the point of view of the desorption phase, a high releasing temperature T_H (up to 500 K), at state 3, is expected to increase the net gas quantity Δn available for circulation. If this gas quantity Δn flows into or out of the cell during Δt_f , the mass flow rate $\dot{m}$ is given by,

$$\dot{m} = \frac{\Delta n}{\Delta t_f} \quad (3)$$

In the whole system, to provide a continuous flow, each phase must have the same duration Δt_f and the four sorption cells must be distributed in the four distinct phases (“quadrature” operation). One cycle period is $T_{cycle} = 4\Delta t_f$, a driving parameter to size the SC cell.

3.2. Sorbent materials

The MOF materials are a promising porous materials because of their high absorbing capacity, and, moreover, they can be tailored for specific applications by exploring different combinations of metals and organic ligands.

In the literature, scarce data regarding absorbent materials for such wide temperature and pressure range (150-500 K, 1-100 bar) is found. For that reason, the adsorption capacity of the various available MOFs was computed using Grand Canonical Monte Carlo (GCMC) [3] and three potential candidates were selected. Those three MOF materials were characterized with nitrogen in a home-made volumetric apparatus in 77-500 K temperature range and 1-100 bar pressure range, described elsewhere [4, 5]. At the moment, only HKUST-1 (or CuBTC) was found to be adequate [6]. One titanium cell (Figure 4a) was filled with this material and its total quantity was measured as a function of temperature and pressure (Figure 4b).

Taking into account these adsorption results and those coming from the thermodynamic analysis (table 2) an optimal operating point is found, while minimizing the radiator area. Let us note that, despite the SC was designed to work up to 500 K, our thermal analysis showed that limiting this high temperature to ≈ 400 K can be safer, being the main consequence a reduction by only 10% of T_{cycle} . The optimal parameters of this solution are indicated in Table 3.

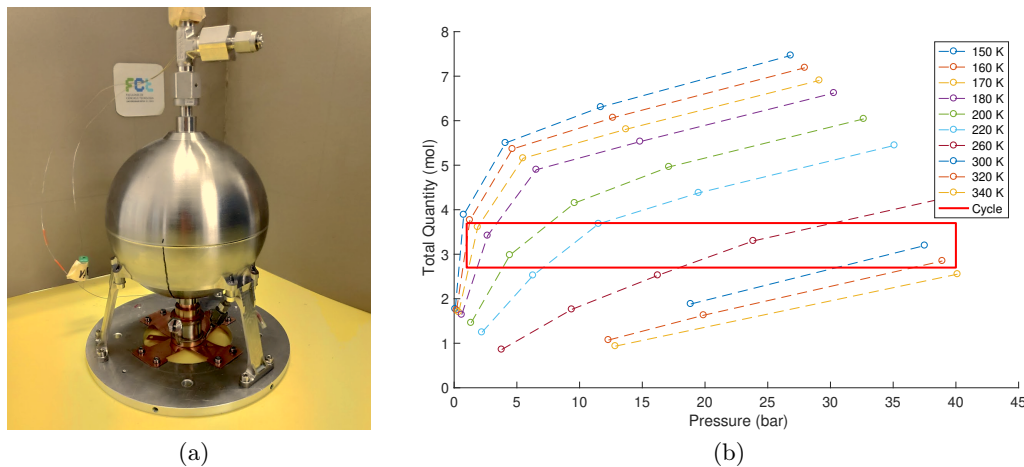


Figure 4: a) One liter titanium sorption compressor cell filled with 377 g connected to the cold source via a H₂ gas gap heat. b) Total quantity measured in the titanium sorption cell as function of pressure. The red square represents an operating cycle.

Table 3: Optimal operating parameters for the sorption compressor.

fluid	Absorbing Temperature	Releasing Temperature	T_{cycle}	Power Budget	Heat Rejection Capacity	Total radiator Area
nitrogen	165 K	380 K	276 min	91 W	40 W	1.57 m ²

3.3. Gas Gap Heat Switch

As previously explained, the temperature of the sorption cell could vary from 160 K to 500 K during its adsorption-desorption cycle. To avoid an unacceptable heat load on the radiator during the heating/desorption phase and to rapidly decrease the sorption cell temperature during the cooling/adsorption phase, the cell has to be connected to the radiator via a controlled thermal link.

The chosen solution was to connect the cell via a gas gap heat switch (GGHS), device particularly suitable for space applications thanks to its simplicity and absence of moving parts [7–10]. In such a device, the high thermal conduction state (ON state, active during cooling phase) is ensured by classical heat transfer through a quite short gas slice (the so called “Gas Gap”) whereas the (very) low thermal conduction state (OFF state, active during heating phase) is obtained by pumping this gas at a sufficiently low pressure (molecular regime, thermal conduction proportional to pressure) to drastically reduce the heat transfer through this gap.

The GGHS consists of two coaxial cylindrical copper blocks aligned and sustained by a 22 mm diameter stainless steel tube (100 μm thickness), the one built and tested is displayed in Figure 5a. The existent gap between these two blocks was obtained thanks to the difference between the thermal dilatation of the copper blocks and the stainless steel tube from welding temperature [11].

Usually in a GGHS, the pumping is obtained by a small cryo-pump thermally connected to the cold block of the switch. In such a case, the working gas has to be chosen considering two issues: the sorption properties of the sorbing material and the thermal conductivity of the working gas. For instance, in our case, none of the best conducting gases (H₂, He, Ne) was able to be adsorbed by an activated charcoal at ≈ 160 K. Hence, another sorbent had to be selected: the metal hydride ZrMn₂, able to absorb H₂ gas (best conducting gas $T > 150$ K) in this temperature range, was selected [12].

The cryo-pump was then filled with 2.6 mg of home-made ZrMn₂ and the thermal conductance was measured as a function of the sorb pump temperature and for different hydrogen charges. After finding the best charge for our purpose (straightest transition ON to OFF), the device was sealed and characterized again. The results of such characterization are displayed in Figure 5b.

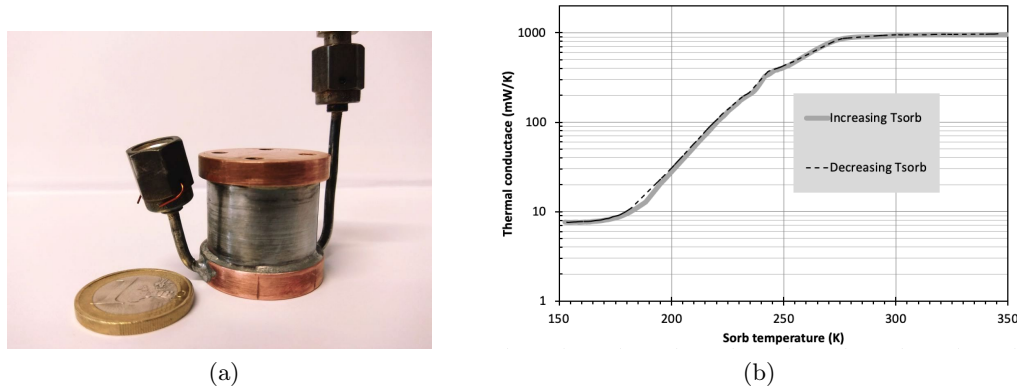


Figure 5: a) Hydrogen GGHS as built. b) Measured thermal conductance of the sealed hydrogen GGHS using ZrMn₂ sorb pump, cold block at 150 K. Note that the ON/OFF ratio is higher than 100.

For a sorb pump temperature higher than 300 K, the thermal conductance is relatively high and becomes independent of the sorb's temperature, indicating that the gas desorbed from the ZrMn₂ achieved a pressure high enough to reach the viscous regime (thermal conductivity independent of the pressure) and, using $Q_p/\Delta T = kA/\Delta$, a gap Δ around 25 μm at 300 K and 30 μm at 77 K would explain this thermal conductance value.

Decreasing the sorb pump temperature, the ZrMn₂ material absorbs the H₂ gas, leading to a pressure reduction. For a sorb temperature lower than 170 K, the thermal conductance is lowered by more than a factor 100 and becomes constant: indicating that the conduction through the gas is negligible compared to the heat transfer along the stainless steel tube. The value obtained (8 mW K⁻¹) is in agreement with the thermal conductance of this tube calculated using the SS thermal conductivity [13] and its geometric dimensions (diameter, thickness and height).

These results show that such a device is perfectly adapted to its objective: with the cryo-pump's temperature at 160 K, the sorption cell can be heated up to 500 K (Phase A & B) without prohibitive heat load on the radiator, whereas, heating it up to 300 K allows an efficient cooling (Phase C & D). An article describing with more details this device will be published elsewhere.

4. Conclusions

A 80 K nitrogen vibration-free cooler was designed to operate with a functional temperature around 80 K with a heat lift of 1.5 W. Among the various possible parameters for the JT stage, a thermodynamic analysis helped us to select a configuration compatible with ESA's requirements. The chosen configuration implies a cycle with a gas pre-cooling interface at 120 K. With these conditions a total radiator's surface of 1.57 m² is estimated.

For the SC, that works with cycles of adsorption-desorption, several materials were tested. At the moment, HKUST-1 (or CuTBC) was found to be the best one and a one litre titanium SC cell was filled with 377 g of this material and its adsorption capacity was measured.

A GGHS able to couple/decouple the SC from an heat-sink, was tested with hydrogen gas as conducting element. The switching between states ON/OFF was successfully achieved using the metal hydride ZrMn₂ in a sealed GGHS. An ON/OFF ratio 1000/8 was obtained, showing that such a device is adapted to its objective.

The performance of part of this cooler (1.5 W@80 K) is under tests.

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