DEVELOPMENT OF A 15 K HYDROGEN-BASED SORPTION COOLER

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ABSTRACT

At the University of Twente, a 15 K hydrogen-based sorption cooler is under development, which has no moving parts and, therefore, is essentially vibration-free. Moreover, it has the potential of a very long life. Although the cooler may operate stand-alone, it is designed to precool a helium-based sorption cooler that establishes 5 mW at 4.5 K, requiring a cooling power of 25 mW at the hydrogen stage. Both coolers use micro-porous activated carbon as the adsorption material. The combination of these two cooler stages needs a total of 5.4 W of input power and is heat sunk at two passive radiators at temperatures of about 50 K and 90 K (1.9 W and 3.5 W, respectively). We developed and built a demonstrator of the helium cooler under a previous ESA-TRP contract, and in 2008 we started a new ESA-sponsored project aiming at the development of the hydrogen stage. In the paper, the preliminary design of this hydrogen-cooler is presented, along with introductory experiments on its Joule-Thomson cold stage.

KEYWORDS: space, cooler, refrigeration, low-noise, long-life, sorption, hydrogen

INTRODUCTION

A new type of vibration-free and long-life cryocooler is under development at the University of Twente. High-pressure gas is supplied by a sorption compressor that operates with a sorber material such as activated carbon. Activated carbon is a material that by its highly porous structure has a very large internal surface so that it can adsorb large quantities of gas. By heating the sorber the gas is desorbed and a high pressure can be established. By expanding this high-pressure gas in a Joule-Thomson (JT) cold stage, cooling can be obtained.

CP1218, *Advances in Cryogenic Engineering: Transactions of the Cryogenic Engineering Conference - CEC, Vol. 55,* edited by J. G. Weisend II

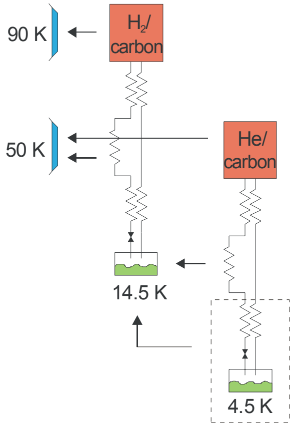

FIGURE 1. Schematic of the helium/hydrogen sorption cooler, which is precooled by two passive radiators at about 50 and 90 K [1].

In a previous ESA-TRP project, we have proposed a sorption cooler for the Darwin mission. Here, a temperature of 4.5 K is required that is established in two steps, see FIGURE 1. First, a sorption cooler operating with hydrogen gas realizes a temperature of 14.5 K. A second sorption cooler operating with helium gas is precooled by this hydrogen stage, and reaches 4.5 K. The hydrogen compressor is thermally linked to a 90 K radiator heat sink. The hydrogen gas is precooled by a 50 K radiator that also serves as the heat sink for the helium compressor. Apart from a few passive valves, this cooler concept has no moving parts and is, therefore, virtually vibration-free. The absence of moving parts also contributes to achieving a very long lifetime. In addition, the cooler operates with limited DC currents so that hardly any electromagnetic interference is generated. In the previous ESA-TRP project, the helium stage was realized and successfully tested [1].

A new ESA-sponsored project was started in 2008 aiming at the development of the 14.5 K hydrogen cooler. In this paper, the preliminary design of this cooler is presented. First, the requirements are reviewed after which the overall system design is discussed. Then, in three subsequent sections the main system components are considered: the sorption compressor plus buffers, the check valves, and the cold stage.

REQUIREMENTS

The requirements and environmental constraints for the hydrogen-stage cooler are listed in TABLE 1. The cooling power of 25 mW is considered to be adequate to precool the helium stage of the Darwin cooler [1] and to deal with the parasitic heat load [2].

TABLE 1. Requirements and constraints of the hydrogen-stage sorption cooler.

Cooling capacity	> 25 mW @ 14.5 K
Temperature stability:	+/- 25 mK for 24 h +/- 50 mK for cooler life time
Life time	5 years in orbit, + 1 year ground test, + 2 years storage
Power consumption (including electronics)	< 100 W
Cooler thermal environment	50 K
Radiator compressor heat-sink levels	90 K and 50 K
Cooler mass (excluding electronics)	< 5 kg

SYSTEM DESIGN

The preliminary design of the 25 mW hydrogen sorption cooler is given in FIGURE 2. The existing 4.5 K helium sorption cooler is included in the picture to illustrate the design aspects of the integration of the two coolers. Compared to our original helium-stage cooler [1], the input power and required radiator area for this cooler have recently been reduced by 30% by incorporating higher-performance carbon [3]. The input required for the hydrogen stage as well as the resulting radiator area have been evaluated including a 25 % design margin. In both coolers, the compressors contain two stages each of which have two parallel cells. The cells of the hydrogen stage are thermally cycled between the heat-sink level of 90 K and 200 K for the first compressor stage and 220 K for the second. As a result, hydrogen is cyclically adsorbed and desorbed, and thus hydrogen gas is pumped from the low-pressure buffer (P_L at 0.1 bar) to the medium-pressure buffer (P_M at 4 bar) and subsequently to the high-pressure side of the cold stage (at 50 bar). The flow direction in this process is controlled by passive valves.

In our preliminary design of the hydrogen cooler, we propose a single radiator temperature level of 90 K for heat sinking of both hydrogen-compressor stages. By splitting the radiator in separate levels for both compressor stages, an improvement in efficiency (and therefore in size reduction of radiator area) of about 10 % can be achieved. In this respect, the optimum temperatures are around 85 K for the first compressor stage and 125 K for the second.

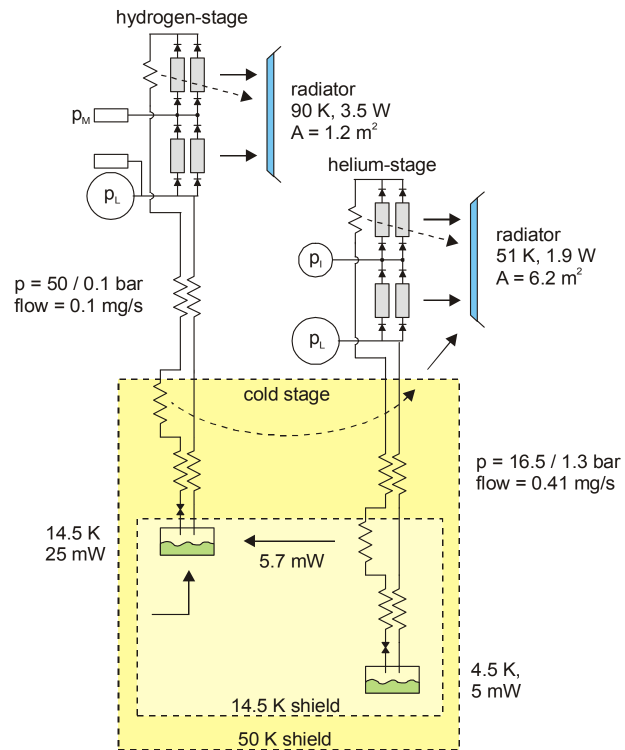

FIGURE 2. Schematic of the preliminary design of the hydrogen sorption cooler. The helium sorption cooler is included to illustrate the total proposed system lay-out for the Darwin mission.

If a higher evaporator temperature is acceptable in the hydrogen cooler, then a higher efficiency can be realized of that cooler. For instance, at 15 K (P_L = 0.13 bar) the efficiency is 7 % higher, and at 18 K (0.45 bar) even 53 %. The radiator area can in these cases be reduced by the same percentages. This argument, however, only makes sense for the hydrogen cooler as a stand-alone cooler. If combined with a helium cooler as in the Darwin mission, the reduction in hydrogen-stage radiator area is overwhelmed by an increase in the radiator area of the helium cooler. If, for instance precooled to 18 K instead of 14.5 K, the helium JT loop would exhibit a 45 % lower cooling power, implying a radiator area of 9.0 m^2. The increase by 2.8 m^2 in the helium-cooler radiator is much larger than the reduction at the hydrogen side, which is only 0.4 m^2. Therefore, in the Darwin cooler we aim to have the helium precooling temperature as low as possible. A limit in this respect is set by the triple point of hydrogen, i.e. 13.8 K. Thus, 14.5 K was chosen as feasible although the required vapor pressure of 0.1 bar will not be simple to realize. A pressure drop in the return line in this case is quite critical; 10 mbar pressure drop results in about 10 % loss in performance. We analyzed the pressure drop contributions in the various system components and concluded that 10 mbar is feasible, the maximum contribution being in the check valves.

SORPTION COMPRESSOR AND BUFFERS

Compressor cells

The design of the compressor cells is similar to that of the helium cooler published before, again using stainless steel 316 [1]. The size, however, is smaller: both compressor stages have diameter 10 mm, length 100 mm, wall thickness 0.15 mm. Each cell contains 8.64 grams of optimized carbon [3]. A flow of 0.1 mg/s can be established by cycling the cells between 90 K and 200 K for the first stage and 220 K for the second. The resulting cycle time for the first stage is 708 s and that of the second stage 1819 s.

Buffers

At the system low and medium pressure, buffers are needed to dampen the pressure variation caused by the asynchronous cycling of the sorption cells. In addition, the low-pressure buffer is used to store the majority of hydrogen gas when the system is stored at ambient temperature. In the hydrogen sorption cooler we intend to use a combination of relatively small buffers that are filled with adsorption material together with an empty somewhat larger low-pressure buffer. The 'sorption buffers' are interfaced to the 90 K radiators and have a significant buffering capacity during operation of the sorption cooler. The empty low-pressure buffer is hardly used during operation of the cooler. Its purpose is to store the hydrogen gas at ambient temperature.

The low-pressure buffer consists of a 100 ml reservoir filled with carbon and an empty reservoir of 1 liter. The medium-pressure buffer is 25 ml filled with carbon. Using these buffers, the pressure fluctuation on the low-pressure side is limited to 5 mbar, corresponding to a boiling-point fluctuation of 0.1 K. In order to realize the required temperature stability, a control scheme similar to that of the helium stage will need to be incorporated [1]. At ambient temperature during storage, the system pressure is 26 bar, and at 90 K in non-operating mode the filling pressure is reduced to 6 bar.

TABLE 2. Leak-rate requirements for single check valve.

	system rate	pressures (bar)	max leak rate	He leak rate at 300 K
helium stage	0.41 mg/s	16.5 / 4 / 1.3	2 μg/s	0.1 μg/s
hydrogen stage	0.1 mg/s	50 /2 / 0.1	0.50 μg/s	0.047 μg/s

VALVES

Apart from other critical requirements such as reliability, the leak rate is one of the most important requirements of the check valves. A leak rate directly affects the net flow through the cooler and reduces the cooling power. In our design, a maximum reduction due to leak rate of 1% is accepted. Since each compressor stage is composed of two parallel cells, and most of the time all valves are closed (flow time is small compared to cycle time [1]), it is fair to set a maximum of 0.5 % per valve. The resulting requirements are listed in TABLE 2. Here, the right-most column gives the maximum leak rate for helium at 300 K. This value is used in test experiments at ambient temperature, and is derived from the maximum leak rate at operating conditions, by taking into account the temperature dependant densities and viscosities of hydrogen and helium. TABLE 2 shows that the requirements for the hydrogen stage are more severe than for the helium stage: the leak rate has to be significantly lower whereas the pressure difference is much higher.

In the helium-stage cooler valves were used that basically consist of a flat boss that fits tightly onto a flat seat [4]. This type of valves functioned well in the helium stage [1], but because of the high flatness required as well as low roughness, we have investigated alternative approaches for the hydrogen-stage cooler. In one of the concepts, the seal is formed by a knife-edge that presses into a soft metal layer. The valves are made of stainless steel, but the knife-edge itself is machined in a thin nickel layer covering the valve seat, see FIGURE 3. To establish the seal, a soft gold layer is deposited on the boss and hand polished afterwards.

The first valve realized in this knife-edge concept showed a very good performance, at 77 K (FIGURE 4) as well as at ambient temperature with repeated cycling (FIGURE 5). In a second run with four more valves, however, we had problems with contamination: so far undefined particles. These newer valves all had leak rates at around the acceptable level but significantly higher than that of the first valve as presented in FIGURES 4 and 5. Currently, we are investigating this issue as well as other concepts to realize small cryogenic all-metal passive valves with a very low leak-rate rate.

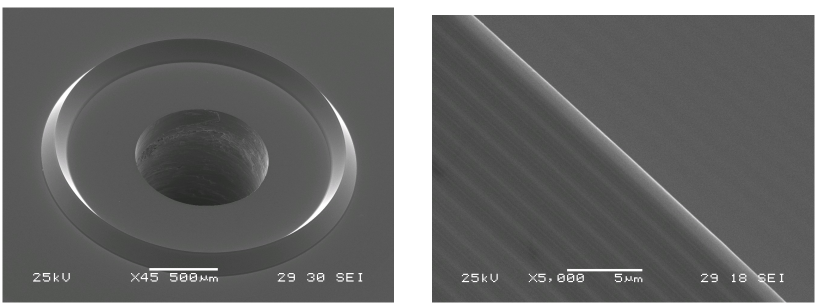

FIGURE 3. Circular knife machined in nickel layer on valve seat; right: detail of the knife edge showing sub-micron rounding.

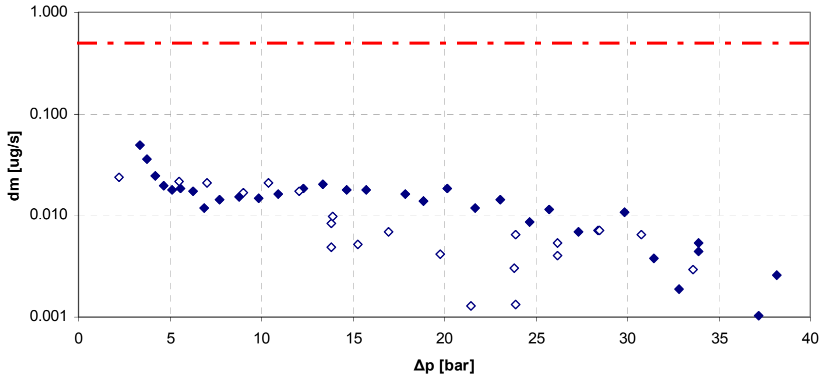

FIGURE 4. Leak rate of the first knife-edge valve measured at 77 K; the dash-dotted line indicates the acceptable level. The detection limit is around 0.01 µg/s. Data is for a pressure sweep up (solid symbols) and down (open symbols).

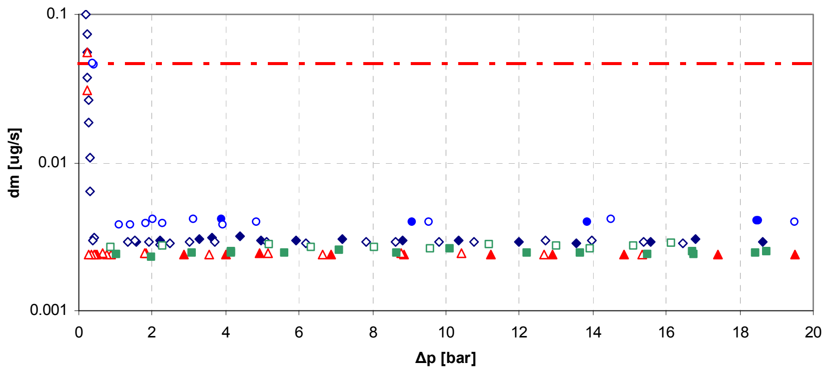

FIGURE 5. Leak rate of the first knife-edge valve measured at 300 K; the dash-dotted line indicates the acceptable level. The detection limit is around 0.003 µg/s. Recorded leak rate after pressure cycling; circles: first cycle; diamonds: after 111 cycles; triangles: after 944 cycles; squares: after 9260 cycles. Data is for pressure sweeps up (solid symbols) and down (open symbols).

COLD STAGE

The general scheme of the cold stage is depicted in FIGURE 6. The counter flow heat exchangers (CFHX) are all configured as tube-in-tube made in stainless steel 316. The heat exchangers (HX) are stainless steel tubing clamped in copper blocks. The aftercooler HX 1 is used to cool the gas leaving the compressor to the compressor heat-sink temperature of 90 K. The precooler, HX 2, is thermally connected to the 50-K radiator and increases the cooling enthalpy of the cold stage. The aim of the anti-clogging filter (HX 3) is to freeze out all remaining impurities just before the gas enters the restriction by cooling the high-pressure gas near to the evaporator temperature. This filter is cooled by a thermal connection to the evaporator (HX 4) using a copper strip. Compressed copper foam is used to increase the contact area between fluid and both bodies. The temperature in the filter should not decrease below 15.5 K because 50 bar hydrogen solidifies at that temperature.

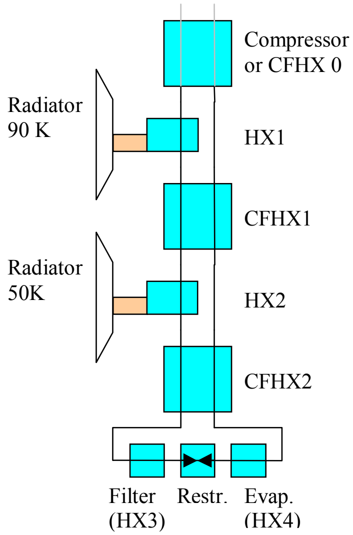

FIGURE 6. Schematic of the hydrogen cold stage. For test purposes, gas is supplied from a pressurized bottle at 300 K in stead of a sorption compressor at 90 K. In that case a counter flow heat exchanger is required between 300K and the first radiator at 90 K.

The filter temperature can be controlled with a heater and sensor or otherwise the thermal resistance of the thermal link to the evaporator should be tuned such that the temperature difference stays above 1 K. The evaporator (HX4) is the main cooling platform. Copper foam is applied to increase the contact area and thus to decrease the temperature difference between the cold liquid hydrogen inside and the copper outside.

A test version of the hydrogen cold stage has been designed allowing for a factor of six higher flow rate and corresponding cooling power (0.6 mg/s and 150 mW, respectively). High-pressure gas is supplied by a pressurized gas bottle at ambient temperature and, therefore, in the test setup an additional counter flow heat exchanger (CFHX 0) is required. The high-pressure gas line is 1/16” tubing (1.59 mm outer diameter, 0.88 mm inner), whereas the low-pressure line is formed by the annular gap to a 1/8" tube (3.18 mm and 2.88 mm, resp.). In order to reduce the pressure drop in the low-pressure line, the outer tube in the CFHX 0 is 1/4" (6.35 mm and 4.55 mm, resp.). The lengths of the various heat exchangers in the test setup are as follows: CFHX 0: 399 mm; HX 1: 80 mm; CFHX 1: 286 mm; HX 2: 120 mm; CFHX 2: 309 mm. The filter (HX 3) and the evaporator (HX 4) are OFHC copper blocks with an internal channel of 5 mm diameter and 30 mm in length, filled with compressed copper foam for increasing the thermal contact area. The Joule-Thomson flow restriction is a sintered stainless steel plug inside a 1/8” VCR coupling. The low-temperature part of the test cold stage is depicted in FIGURE 7.

This test version of the cold stage was placed in a vacuum enclosure, in which a 2-stage GM cooler was mounted for cooling HX 1 and HX 2 as well as a thermal radiation shield. High-pressure gas was supplied from a gas bottle and reduced to a pressure of about 50 bar. The outlet of the system was pumped by a 2-stage membrane pump to establish a sub-atmospheric pressure of around 0.1 bar. This configuration simulates that of the hydrogen sorption cooler as depicted in FIGURE 2. In the experiments, HX 1 and HX 2 were stabilized at 90 K and 50 K, respectively. The thermal radiation shield surrounding the whole stage was on average 65 K. Results of introductory experiments are summarized in TABLE 3. The setup quite easily reached the set point of 14.5 K. The flow rate is

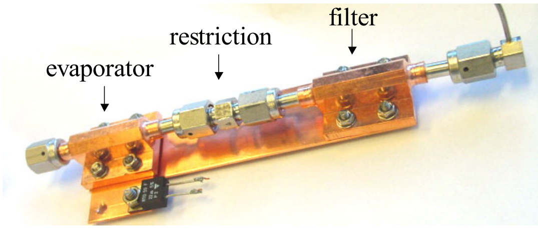

FIGURE 7. Low-temperature section of the test cold stage.

TABLE 3. Experimental results obtained on test cold stage

HX 1 (K)	HX 2 (K)	T filter (K)	T evap (K)	flow (mg/s)	high pres (bar)	low pres * (bar)	P gross (mW)	P applied (mW)
90	50	18.25	14.5	0.51	50.25	0.0842	133	121

* low pressure measured at outlet

somewhat below the design value of 0.6 mg/s, but very well acceptable for test purposes. In these experiments, the evaporator was stabilized at 14.5 K, slightly above the actual boiling point. Taking into account a pressure drop of the order of 10 mbar in the return line, the low pressure at the outlet corresponds to a boiling point of around 14.3 K. TABLE 3 also presents the theoretical gross cooling power combined with the power applied to the evaporator in the actual experiments.

CONCLUSION

The preliminary design of a 25 mW @ 15 K hydrogen-based sorption cooler was described. Compressor cells were designed but have to be manufactured and tested. A check-valve design was made based on a metal-to-metal knife-edge seal. Promising results were obtained on a prototype valve, and repeatability is now under investigation. The cold-stage design was validated by experiments performed on a demonstrator having about 5 times the targeted cooling power. The critical design review is expected by end of 2009, and the full system should be ready for test by end of 2010.

ACKNOWLEDGEMENTS

This work is supported by the European Space Agency under contract 21348/07.

REFERENCES

1. Burger, J.F., Brake, H.J.M. ter, Holland, H.J., Meijer, R.J., Veenstra, T.T., Venhorst, G., Lozano-Castello, D., Coesel, M. and Sirbi, A., "Long-life vibration-free 4.5 Kelvin sorption cooler for space applications," *Review of Scientific Instruments* **78** (6) 065102 (2007)
2. European Space Agency, Statement of work, Hydrogen Sorption Cooler, Reference: TEC-MCT/2007/3572/ln/ASP, 10-10-2007.
3. Burger, J.F., Holland, H.J., Meijer, R.J., Brake, H.J.M. ter, Doornink,J., Sirbi, A. and Linder, M., "Further developments on a vibration-free helium-hydrogen sorption cooler," in *Cryocoolers 15, Proceeding of the 15th Cryocooler conference*, edited by S.D. Miller R.G. Ross jr., ICC Press Boulder, USA. isbn. 13-978-1-934021-01-9, 2009, pp. 23-30.
4. Veenstra, T.T. *et al.*, *Cryogenics* **47**, pp.121-126 (2007).