Further Developments on a Vibration-Free Helium-Hydrogen Sorption Cooler

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ABSTRACT

In our continuous effort on the development of a passively precooled two-stage 4.5 K / 14.5 K helium-hydrogen sorption cooler, a number of important development steps were made. Firstly, an improved high-density activated carbon was used for the fabrication of four new sorption cells. Tests with these new cells showed that because of increased efficiency, the required passive radiator area for this cooler reduced by a factor of 1.3. Secondly, it was shown that this cooler architecture can easily be used to reach lower (or higher) temperatures. Without hardware changes, the cold temperature was reduced from 4.5 K to 3.1 K. Thirdly, long-term experiments were carried out on the cooler. In two separate periods of two and four months of continuous operation, no change at all was observed in the cooler performance. Fourthly, clogging effects were analyzed that occurred after a 15 months storage period of the cooler at 300 K. We concluded that hydrogen diffusion out of the stainless steel components should be prevented. Finally, a design of an integrated compact cooler chain was presented, which consists of a 50 K Stirling cooler and the helium-hydrogen sorption cooler. This package may be used in the future to test the sorption cooler technology in a zero-gravity environment.

INTRODUCTION

The University of Twente is working in a continuous effort on the development of a passively precooled two-stage 4.5 K / 14.5 K helium-hydrogen sorption cooler. This cooler has no moving parts and is, therefore, essentially vibration-free. It is a favorite option for space missions such as ESA's Darwin and Xeus missions, which require long-life and vibration-free cooling to low temperatures.[1]

The selected cooler design consists of a hydrogen stage cooling from 80 K to 14.5 K and a helium stage establishing 5 mW at 4.5 K, see Fig. 1.[2] Both stages use micro-porous activated carbon as the adsorption material. The two cooler stages need only a few Watts of input power and will be heat sunk on two passive radiators at temperatures of about 50 K and 80 K, radiators which should be constructed at the cold side of the spacecraft. We have developed and built a demonstrator of the helium stage under an ESA-TRP contract. The design of this cooler, together with detailed experiments, was presented previously at the ICC in 2006.[3]
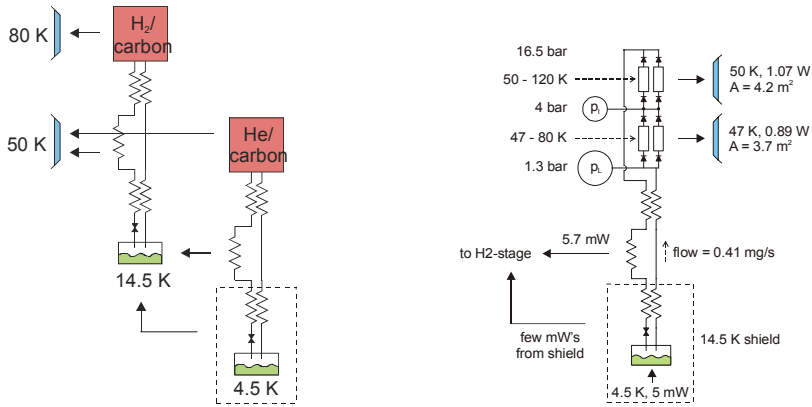
Figure 1. (a) Schematic picture of the proposed helium / hydrogen sorption cooler, which is precooled by two passive radiators at about 50 K and 80 K. (b) More detailed design of the helium sorption cooler.

Since then, we have monitored a number of aspects that may affect the long-term operation of this cooler. These aspects will be discussed in this paper. Furthermore, we have replaced the four sorption cells with new cells that contain a new high-density activated carbon, which results in an efficiency improvement by a factor of about 1.3. Measurements with these new cells are presented. In addition, experiments are presented that illustrate the ability of this cooler to reduce the low temperature in a flexible way, to approximately 3 K. Finally, we will present the design of an integrated compact cooler chain that consists of a Thales 50 K Stirling cooler and the helium-hydrogen sorption cooler.

For general details about the operation of sorption coolers, the reader is referred to the literature.[4, 5]

TESTS WITH IMPROVED SORPTION CELLS

A passively precooled sorption cooler for space applications has a number of clear advantages over alternative mechanical cooler options, such as no vibration, long or infinite lifetime, and a very low input power. The price to pay for these advantages is that a passive radiator is required. The activated carbon that is used in the compressor cells strongly influences the performance of the cooler, and hence the required radiator area. The carbon used so far was optimized especially for our application by the University of Alicante; it is a monolithic highly micro porous carbon of high density made from anthracite.[6] From previous work[5] we knew that activated carbons fabricated from synthetic precursors could result in even higher carbon densities (up to 1.1 g/ml), which would reduce the radiator area most likely. An important reason for this performance improvement is the very low void volume of such carbons. We were able to obtain this type of material and we built four new sorption cells with it.

Apart from the new carbon, we tested a few fabrication improvements of the cells. The existing sorption cells in the cooler were replaced with the four new cells. In addition, a leaking check valve was replaced, which forced us in previous measurements to test the cooler with three instead of four operating sorption cells.[2] After replacement of the sorption cells and the check valve, the cooler was cleaned and re-filled with high-purity helium gas. After cool-down of the system to 50 K using a GM cryocooler, the sorption cooler was started; it cooled down successfully to 4.5 K. Next, important operating parameters such as the compressor low and high temperature and the intermediate pressure were varied to find the optimum operating parameters (i.e. minimum radiator area). A typical measurement of the system cooling to 3.15 K is given in Fig. 2. Table 1 compares the resulting performance numbers of the cooler for the previous and present activated carbon. Clearly, a reduction of a factor of 1.3 is obtained for the resulting radiator area.
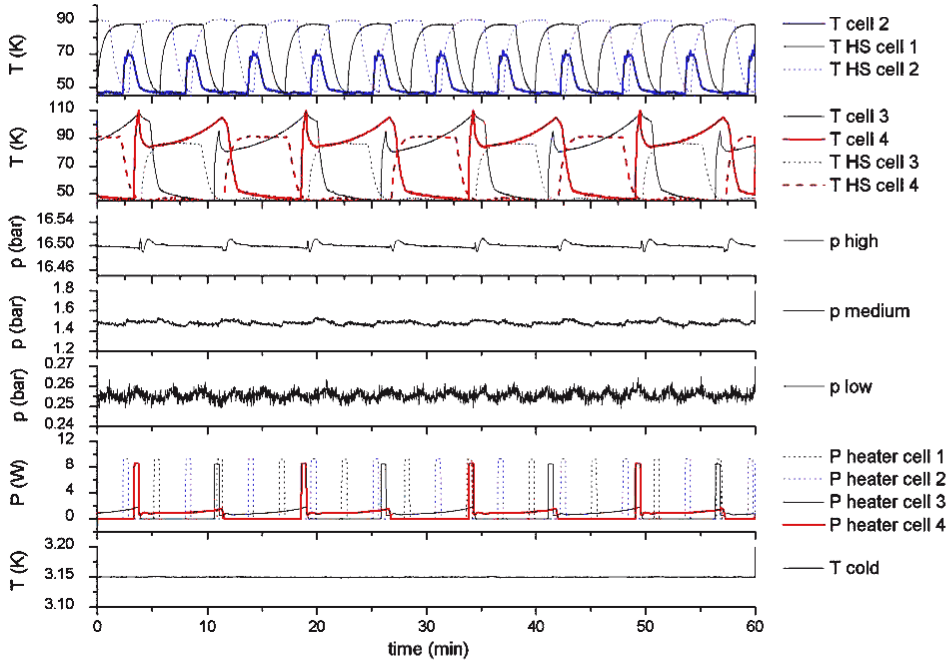
Figure 2. Typical measurement of the helium sorption cooler, operating with a low pressure of 0.27 bar and a (very stable) cold temperature of 3.15 K. From top to bottom: compressor and heat switch temperatures of the first stage compressor cells, compressor and heat switch temperatures of the second stage compressor cells, high, medium and low pressure, compressor input powers, cold temperature.

VARIATION OF THE LOW TEMPERATURE

The cold temperature is determined by the low pressure in the return line of the cold stage, which controls the boiling point of the evaporator. For a low temperature of 4.5 K, the low pressure is about 1.3 bar. In principle, this pressure can be lowered by filling the sorption cooler with less gas so that during operation a lower pressure is present in the low pressure buffer. The low pressure can be reduced as long as no significant pressure drops arise in the low pressure lines, and as long as the first compressor stage is able to pump sufficiently on the low pressure line (for a certain heat sinking temperature the sorption pumping capacity reduces with a

Table 1. Comparison of the resulting performance numbers of the sorption compressors.

	test results previous carbon	test results new carbon
1st stage compressor		
sink temperature	47.1	50 K
cycle period	289 s (single cell)	600 s (two cells)
average input power in compressor stage	0.89 W	0.88 W
resulting radiator area (assuming emissivity = 0.8)	4.2 m²	3.1 m²
2nd stage compressor		
sink temperature	50.5 K	52 K
cycle period	975 s	1436 s
average input power in compressor stage	1.07 W	0.99 W
resulting radiator area (assuming emissivity = 0.8)	3.7 m²	3.05 m²
combined 1st and 2nd stage compressor		
average input power	1.96 W	1.85 W
resulting radiator area (assuming emissivity = 0.8)	7.9 m²	6.2 m²

Table 2. list of the experimental results in which the temperature is reduced in steps from 4.5 K to 3.1 K.

p low (bar)	p middle (bar)	T cold (K)	P cold (mW)	TL1 (K)	TL2 (K)	P in (W)	Area (m^2)	Area/Pcold (m^2/mW)
1.27	4.6	4.5	4.5	50	52	1.85	6.2	1.38
0.78	4	4	4.6	48	52	2.29	8.5	1.85
0.47	2.63	3.55	4.7	48	50	2.94	11.7	2.49
0.27	1.45	3.15	5	45	45	3.15	17.7	3.54
0.23	1.5	3.1	4	45	45	2.75	15.4	3.85

reduction of the low pressure, resulting in a faster cycling of the cells).

We decided to demonstrate experimentally to what level the low temperature can be reduced. Apart from a reduction of the amount of He gas in the system and an adaption of the control settings in the software, no other hardware changes were made. Table 2 shows a list of the experimental results in which the temperature is reduced in steps from 4.5 K to 3.1 K. A temperature of 3.1 K was the lowest value that could be reached with the present set-up; at this temperature the first compressor stage was just able to maintain the low pressure of 0.23 bar. With minor modifications in the set-up, a temperature as low as 2.5 K can be achieved with [4]He. (see the discussion below).

Fig. 3 shows a plot of the specific radiator area that is derived from the measured cooler performance, which is compared to previously modelled values. The difference between the measured and modelled values increases for lower temperatures, which we can explain due to two different effects. Firstly, at 4.5 K the cooler operating parameters were optimized experimentally to obtain a minimum radiator area (i.e. the cooler control settings were varied to find the best performance). This optimization was not carried out for the lower temperatures and, therefore, the resulting radiator area is not optimized. This sub-optimal operation will be stronger for lower cold temperatures. Secondly, for lower temperatures the first compressor stage performance is deteriorating due to internal pressure drops, an effect which especially occurred when reducing the low temperature from 3.15 K to 3.1 K. Such low temperatures (and even lower temperatures down to 2.5 K) could be reached without a performance reduction if a lower mass flow could be selected (by replacing the flow restriction) or by adding one or more sorption cells in the first stage compressor.

From the results it can be concluded that the sorption cooler technology is very suitable for reaching lower (or higher) cooling temperatures with the same cooler architecture.
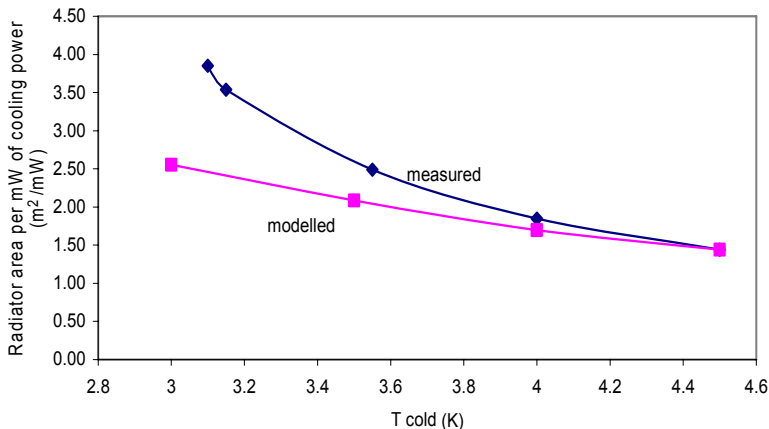

Figure 3. Plot of the specific radiator area as a function of the cold temperature of the cooler.

LONG TERM OPERATION OF THE SORPTION COOLER

After the initial tests on the sorption cooler which were described previously[2], a number of steps were made with the cooler that provide information about various aspects of the long term operation of the sorption cooler. In a period of two years, the following steps were made:

1. After the initial cooler tests[2], the cooler was left running for a period of two months.
2. The sorption cooler and the precooling GM cooler were switched off for a period of about 15 months, leaving the sorption cooler unchanged at 300 K in our lab.
3. When the new sorption cells were ready to replace the old cells, we first wanted to check if the sorption cooler with the old cells would still restart properly after the 15 months of storage at 300 K.
4. After this restarting test, the old sorption cells were replaced with the new cells and the tests were carried out that were described in the previous sections.
5. After these tests, the sorption cooler was left running for a period of 4 months (until the day of writing this paper).

During the two and four months of continuous cooler operation (steps 1 and 4 above), *we did not observe any change in the cooler performance whatsoever*. This also means that we did not observe any change or degradation of the activated carbon, the check valves, or the gas-gap heat switches. Also, clogging of the cold stage did not occur during normal continuous operation of the cooler.

However, after restarting the sorption cooler after 15 months of storage (see step 3 above), significant clogging problems of the cold stage occurred; stable cooling at 4.5 K with the full cooling power could not be obtained anymore. These problems are discussed in more detail in the next section.

ANALYSIS OF CLOGGING EFFECTS

In the initial measurements before the 15 months storage period, clogging was only once observed in a special situation. The cooler had operated at 4.5 K without any clogging for about 10 days, when we deliberately and rapidly heated the coldest part of the counterflow heat exchanger from around 5 K to 15 K (while the JT and evaporator were still at 4.5 K!). After this (very local) heating action, suddenly clogging of the JT restriction occurred; it appeared later that the flow had reduced to approximately 25% of its original value. We analyzed the situation and expected that small amounts of frozen hydrogen in the coldest parts of the counterflow heat exchanger were evaporated due to the local heating action, and transferred to the JT restriction that was still at 4.5 K. Here it could freeze again and block the narrow pores of the JT plug. After stabilization of the system in which the cooling and input powers had dropped to 25% of their original values, the system was left in this condition for one night. A gradual increase in the cooling power could be observed (from 1.15 mW to 1.6 mW in 20 hours), indicating a movement of the contamination out of the JT restriction. Then, the restriction was manually heated to 14.5 K for about one hour. After this step, the cooling power returned to the original 4.5 mW at 4.5 K: the contamination was apparently evaporated from the JT. The fact that a temperature of 14.5 K was sufficient to clean the flow restriction confirms the idea that hydrogen was the contaminating gas (the triple point of hydrogen is 13.8 K). This experiment shows that small amounts of contaminant gases can be frozen and maintained inside the cold counterflow heat exchangers, thereby not harming the cooling power – as long as the contaminants do not move into the JT flow restriction.

Since then, the 4 K sorption cooler was stored in our lab for 15 months at 300 K with the original batch of helium inside. After these 15 months, the GM precooler was restarted to cool the sorption compressors to 50 K. After starting of the sorption compressors, it appeared that we could not successfully reach 4.5 K with 4.5 mW of cooling power anymore. Either the system clogged completely after cooling below 13K, or it clogged initially partially at 4.5 K and later

completely. We then tried to measure the hydrogen concentration in the helium gas of the sorption cooler using a mass spectrometer, calibrated for low concentrations of hydrogen in helium gas. We measured a hydrogen concentration on the order of 40 ppm. We estimated the original concentration of hydrogen in the system at 0.1 ppm; this is based on the 6.0 purity helium gas that was used to fill the system. Apparently, a hydrogen concentration increase from 0.1 to 40 ppm is sufficient to move from clogging-free operation to a situation of problematic clogging. This hydrogen concentration increase can most likely be explained by hydrogen diffusion out of the metal elements of the cooler while it was stored at 300 K; such diffusion will not occur if the cooler is operating at 50 K (hydrogen diffusion is strongly dependent on the temperature and is much less at cryogenic temperatures).

To prevent outgassing of hydrogen out of the metal elements of the cooler during storage of the cooler at 300 K, a careful bake-out procedure should be applied to these elements prior to use. A similar procedure can be applied that is also used to bake-out UHV components. We expect that this is sufficient to prevent hydrogen outgassing. As an alternative measure, hydrogen gettering in the buffers may be applied.

DESIGN OF A COMPACT STIRLING – SORPTION COOLER CHAIN

A passively precooled sorption cooler is a favorite option for future space missions that require long-life and completely vibration-free cooling to low temperatures. Examples of such missions are ESA's Darwin and Xeus missions. ESA has indicated that early tests in a space environment are desired, to gain experience and reduce the risks of using this new cryocooler technology in an expensive mission. In a small project funded by ESA, we made a conceptual design of a cooler chain consisting of a Stirling precooler plus the helium-hydrogen sorption coolers. This compact system might be used for tests on the International Space Station or in another small space mission to study the effect of the zero-g environment on the cooler behaviour, in particular on two-phase flow and evaporation effects in the cold stage.

Fig. 4 shows a schematic lay-out of the cooler chain. The Stirling cooler replaces the large passive precooling radiator that is required for complete vibration-free cooling. We proposed to
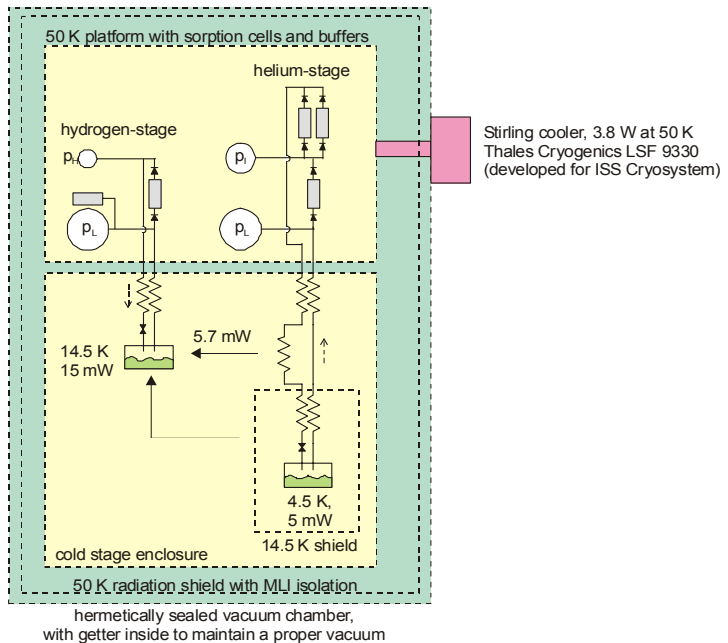

Figure 4. Schematic lay-out of the compact Stirling – helium/hydrogen sorption cooler chain.
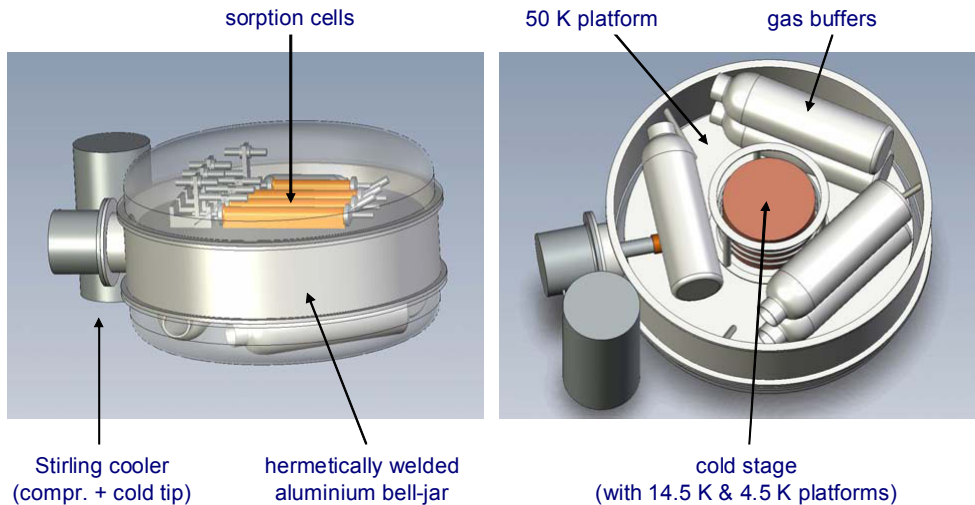
Figure 5. Conceptual drawing of the compact and light-weight aluminium bell jar with the sorption coolers inside, and the Stirling cooler connected from the outside through the collar to the 50 K platform.

use the Thales LSF 9330 cooler, originally developed for cooling of Cryosystem on ISS. The Stirling cooler cools an aluminium platform at 50 K that contains the sorption cells of the helium *and* hydrogen sorption coolers. This sorption cooler architecture is slightly different from the original architecture, where the hydrogen sorption compressor is heat sunk at 80 – 100 K. In combination with a mechanical cooler a simple configuration arises if the hydrogen sorption compressor is heat sunk at 50 K, together with the helium cells. In this case, one small sorption cell can drive the miniature hydrogen cold stage. The hydrogen cold stage elements below 50 K (which would be an important study item in such a test) remain identical as compared to the originally proposed configuration for Darwin. Notice that in combination with passive precooling it is *not* attractive to run the hydrogen sorption cooler from 50 K: this would significantly increase the required radiator area!

Fig. 5 shows a conceptual drawing of the compact and light-weight aluminium bell jar; it was designed for tests in ESA's Columbus laboratory on ISS. The total mass, including electronics, would be approximately 20 kg. The compact cooler chain provides cooling at 50 K, 14.5 K and 4.5 K, which is available for cooling of small instruments in the (test) mission.

CONCLUSIONS

A number of new experimental and design steps were made in the continuous effort of the University of Twente to develop the passively precooled vibration-free 4.5 K / 14.5 K helium-hydrogen sorption cooler for space applications.

- Test results with a new high-density carbon show that the cooler efficiency is improved, which results in a reduction of the specific radiator area with a factor of 1.3.
- It was shown that the sorption cooler technology is very suitable for reaching lower (or higher) cooling temperatures than 4.5 K, using the same cooler architecture. Without any hardware change a cold end temperature of 3.1 K was reached.
- Long term experiments were carried out with the sorption cooler. During two periods of two and four months of continuous cooler operation, no change in the cooler performance was observed in more than 20000 compressor cycles that were made.
- During normal operation no problems with clogging of the JT were observed. However, after 15 months of storage at 300 K the cooler showed significant clogging problems.

Hydrogen diffusion out of the stainless steel walls is the most likely cause of this problem. With proper bake-out procedures this can probably be prevented.

- The design of an integrated compact cooler chain was presented, which consists of a Thales 50 K Stirling cooler and the helium-hydrogen sorption cooler. The total package, including compact vacuum chamber and electronic controller, has a mass of less than 20 kg, requires less than 150 W input power, and may be used to test this cooler chain in space.

In the period 2008 – 2010 we are working on the development of the hydrogen sorption cooler: system modelling and design, breadboarding and test activities on component level, and development of a full functioning breadboard model (aiming at TRL level 5).

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