Vibration-Free 4.5 K Sorption Cooler

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ABSTRACT

At the University of Twente, a breadboard 4.5 K helium sorption cooler was developed which has no moving parts and, therefore, is essentially vibration-free. Moreover, it has the potential of a very long lifetime. This cooler is a favorite option for future missions such as ESA's Darwin mission, which is a space interferometer consisting of a few free flying telescopes. Because of the optics involved in Darwin, hardly any vibration can be tolerated.

The cooler consists of a hydrogen stage cooling from 80K to 14.5K and a helium stage establishing 5 mW at 4.5 K. Both stages use micro-porous activated carbon as the adsorption material. The two cooler stages need about 3.5 W of total input power and are heat sunk at two passive radiators at temperatures of about 50 and 80 K — radiators which are constructed at the cold side of the spacecraft.

We developed, built and tested a demonstrator of the helium stage under an ESA-TRP contract. This demonstrator has four sorption compressor cells in two compressor stages. Test experiments on this cooler showed that it performs within all specifications imposed by ESA. The cooler delivered 4.5 mW at 4.5 K with a long-term temperature stability of 1 mK and an input power of 1.96 W. The exported vibrations are much lower than the required 1 $\mu N/\sqrt{Hz}$. So far, the cooler has continuously operated for a period of 2.5 months and has not shown any sign of performance degradation.

INTRODUCTION

A number of future scientific space missions will require reliable cryogenic cooling systems that can operate without producing mechanical vibrations. An example is ESA's Darwin mission[1]. Darwin is an instrument with the explicit purpose of detecting other earth-like worlds, analyzing their characteristics, determining the composition of their atmospheres, and by doing so, establishing their capability to sustain life as we know it. It is a space interferometer consisting of a few free flying telescopes with a baseline of several hundreds of meters. The optical paths between the telescopes are controlled and stabilized to less than 10 nm by making use of micro-Newton ion thrusters that operate in a control loop in combination with RF, optical and laser metrology. To guarantee the pointing and dimensional stability, no vibration of the optical system with integrated cryocoolers can be tolerated. As a consequence, zero-vibration is one of the central requirements for the cryocooler.

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Table 1. Summary of cryocooler requirements for Darwin[1,2].

cooling power and cold-stage temp.	5 mW @ 4.5 K
radiative precooling power and temperature	1. < 2.5 W @ 50 K, resulting in max. 9.1 m^2 radiator area (or scaled to other temperatures using T^4 law) 2. < 200 W @ 300 K on spacecraft bus
exported mechanical vibrations	< 1 μN/√Hz for f > 0.1 Hz or < 1 μN RMS
input power	< 200 W
mass target	< 10 kg
temperature stability	< 1 mK for 1 hour, < 10 mK for 2 weeks, < 0.1 K for lifetime
lifetime	> 5 years
others: continuous operation; resistant to launch loads; resistant to radiative environment	

In 2003, a TRP study was granted by ESA to the University of Twente (UT) to develop a breadboard helium sorption cooler in order to demonstrate the feasibility of this vibration-free technology. The sorption cooler that we had proposed consists of a sorption compressor that drives a JT cold stage, in combination with passive radiative precooling to below 50 K. Such sorption cooler has no moving parts and is, therefore, essentially vibration-free. In addition, the absence of moving parts also simplifies scaling down of the cooler to small sizes, and it contributes to achieving a long lifetime.

At ICC13 in 2004, different cryocooler options and sorption cooler architectures were compared fo missions such as Darwin, and a system design was proposed for the 4.5 K sorption cooler[2]. After that, this system design was further developed and an advanced breadboard version of the helium sorption cooler was designed, built and tested. This paper presents the resulting cooler, together with the most important test results. The requirements for this cooler, as given by ESA, are summarized in Table 1[1,2]. Since 2004, the specified cooling power was reduced by a factor of two (from 10 mW to 5 mW). Also, the maximum radiator area was reduced by a factor of two. [2]

For general details about the operation of sorption coolers, the reader is referred to the literature.[3, 4]

SYSTEM DESIGN

The selected cooler design consists of a hydrogen stage cooling from 80 K to 14.5 K and a helium stage establishing 10 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 are heat sunk at two passive radiators at temperatures of about 50 K and 80 K — radiators

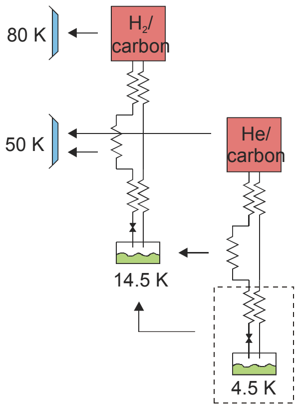


Figure 1. Schematic picture of the proposed helium / hydrogen sorption cooler, which is precooled by two passive radiators at about 50 K and 80 K.

which are constructed at the cold side of the spacecraft. Intrinsic advantages of this system design are:

- The system has no moving parts. Therefore: 1) it is vibration-free; 2) it has a long lifetime; 3) it is scalable to small sizes and cooling powers.
- The cooler has a very small input power of a few watts.
- Separation of the compressor and the cold stage is possible.
- The compressor is operating at the cold side of the spacecraft so that no thermal or fluidic interfacing is required from the cold stage to a compressor in the warm service module.
- There is intrinsic redundancy in the compressor design if enough sorption cells are present (one or more cells can be lost without affecting the cooler performance).
- The efficiency of these sorption coolers is virtually independent of cooling power. Therefore, relatively small radiator areas can be achieved if the required cooling power at 4.5 K can be minimized.

Clearly, a significant cold radiator area is the price that must be paid for these advantages. Minimization of this radiator area can be achieved by the following factors:

- Minimization of the required cooling power at 4.5 Kelvin. This can be achieved by using as much as possible the precooling power at 14.5 K for cooling away the radiative and conductive heat losses on the 4.5 K stage. The radiator area scales approximately linearly with the required cooling power at 4.5 K
- Increase of the cold-end temperature can also reduce the radiator area. An increase of the temperature from 4.5 K to 7.5 K, for instance, reduces the radiator area with approximately a factor of two (for the same cooling power).
- Improvement of the activated carbon will most probably result in a reduction of the radiator area; we estimate that an improvement of a factor of 1.5 can be achieved. An ESA-funded project is currently running at the UT, in which a new carbon monolith will be tested in the sorption cooler.

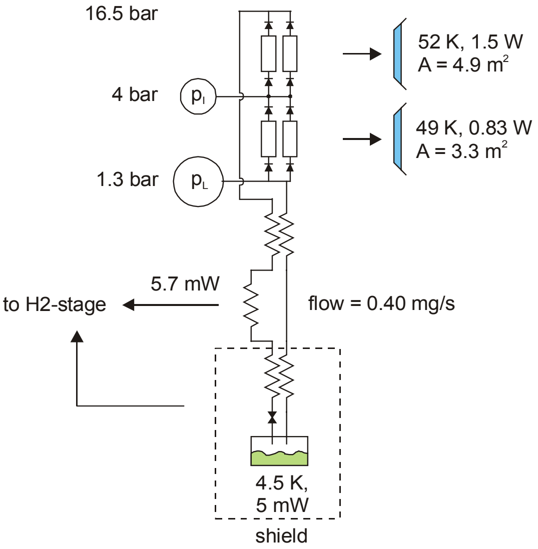


Figure 2. Schematic of the developed breadboard helium sorption cooler. The cooler applies 2 x 2 sorption cells and delivers 5 mW at 4.5 K.

At ICC13 in 2004, we presented a design which consisted of 2 x 6 cells for the helium stage and 2 x 2 cells for the hydrogen stage, providing 10 mW at 4.5 K. This relatively large number of cells resulted from conservative assumptions. After more detailed dynamic modeling of the sorption cells, it was concluded that the number of sorption cells in the helium stage can readily be reduced to 2 x 4 cells. Furthermore, it was agreed with ESA to cut the net cooling power to 5 mW. By reducing the cooling power to 5 mW, the required number of cells could be further reduced to 2 x 2 cells. Fig. 2 shows the resulting design of the helium stage. A breadboard version of this cooler design was developed in the last two years, and will be further discussed in this paper.

DEVELOPED COOLER COMPONENTS

This section presents the designs of the most important building blocks of the sorption cooler: the sorption compressor cells, the check valves, the cold stage and the control system.

Sorption compressor cells

Figure 3 shows the design of a sorption compressor cell, together with a mounted check valve unit which contains the two check valves that interface to the compressor cell. The design of the compressor cell is identical for the two compressor stages, although they are operated at somewhat different conditions. The mass of the compressor cell is 420 grams excluding the check valve unit and 500 grams including it. It is fabricated entirely of stainless steel 316 parts, except for the activated carbon, the heater and the temperature sensor.

Fluidic interfacing of the compressor cell to the check valve unit is done via a Swagelok 1/8” VCR connection. Similar connections are applied to interface the check valve unit to the two pressure lines. Thermal and mechanical interfacing of the compressor cell to the heat sink plate (i.e. the radiator) is done via 16 bolts, which can be screwed in two lines of 8 bolts into the bottom of the compressor cell. These bolts guarantee good thermal contact to the radiator. The electrical interface of a compressor cell connects three parts: the heater, the gas-gap actuator and the thermocouple.

Figure 4 shows a schematic picture of the inside parts of the cell. The inner compressor container is filled with an activated carbon monolith, which was especially optimized for use in this sorption cooler. The inner compressor container is supported in the outside heat sink

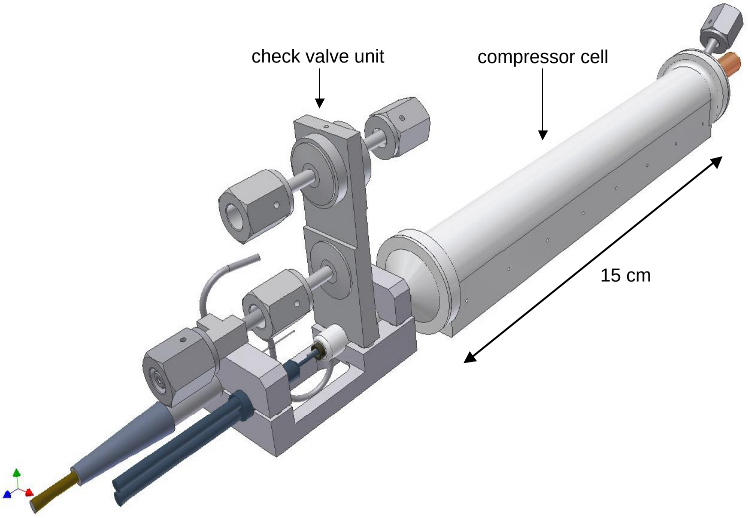


Figure 3. Design of a sorption compressor cell with integrated check valve unit.

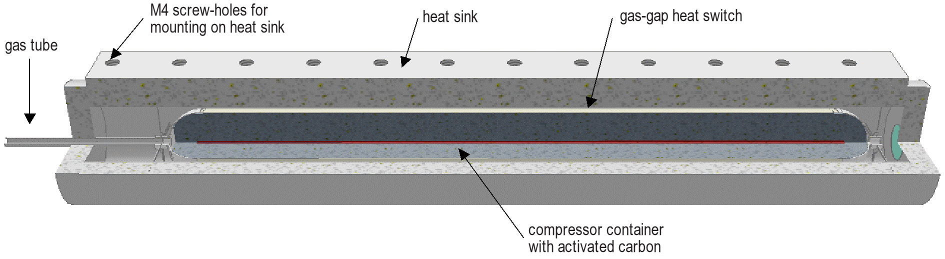


Figure 4. Schematic picture of the inside parts of the compressor cell.

construction, with a narrow gas-gap heat switch in between.[3, 4] The gas pressure in the narrow gap of the gas-gap heat switch can be varied to yield a relatively high or low conduction between the inner container and the heat sink. In this way, the inner container can be thermally isolated from the heat sink during the heating phase of the container and it can be thermally connected to the heat sink during the cooling phase of the container.

Check valves

The design of the check valve unit is also shown in Fig. 3; in this picture the check valve unit is mounted on the compressor cell. The check valve unit contains the two check valves that interface to the compressor cell. The all-metal internal design of the check valves is such that it fulfills all the requirements as given in the introduction of this paper, as well as the very strict operating requirements which are imposed by the system design. Among others, these include: cryogenic operation, low leakage flow in closed direction, low pressure drop in forward direction, tolerant to contamination coming from the compressor cell, and reliable use for over 500,000 open-close cycles. A number of different breadboard tests on the check valve were carried out to verify that the design could meet these requirements. More details on the check valve design are to be published elsewhere.[5]

Cold stage

The design of the cold stage is given in Fig 5. The total mass of the cold stage is 650 grams; dimensions are given in the figure. The cold stage is constructed around two supporting frames, one at 50 K and one at 14.5 K, which are fixed together via a Kevlar cable system. This Kevlar cable system produces a completely fixed structure which is resistant to launch forces.

The first and the second counterflow heat exchanger are spiraled inside both supporting frames, and also fixed via Kevlar cabling. The counterflow heat exchangers are constructed as tube-in-tube, with a 1/16” inside a 1/8” tube. Both heat exchanger lengths are approximately 100 cm.

The JT flow restriction is fabricated of sintered metal, and tuned accurately to the correct mass flow at 4.5 K. The copper evaporator has a fine copper matrix inside to guarantee a good thermal contact to the flow of liquid helium when it is being evaporated. The mass of the evaporator itself is very small, about 25 grams.

The radiator area required to cool the sorption compressor scales linearly with the required cooling power at 4.5 K. By minimizing the parasitic thermal loads at 4.5 K, virtually all cooling

Table 2. Calculated losses on the 4.5 K cold stage.

effect	*loss*
heat exchanger loss (conduction + efficiency-loss)	80 μW
conduction loss through Kevlar cables	30 μW
conduction loss through electrical cables	10 μW
radiation loss	10 μW
Total	**0.13 mW**

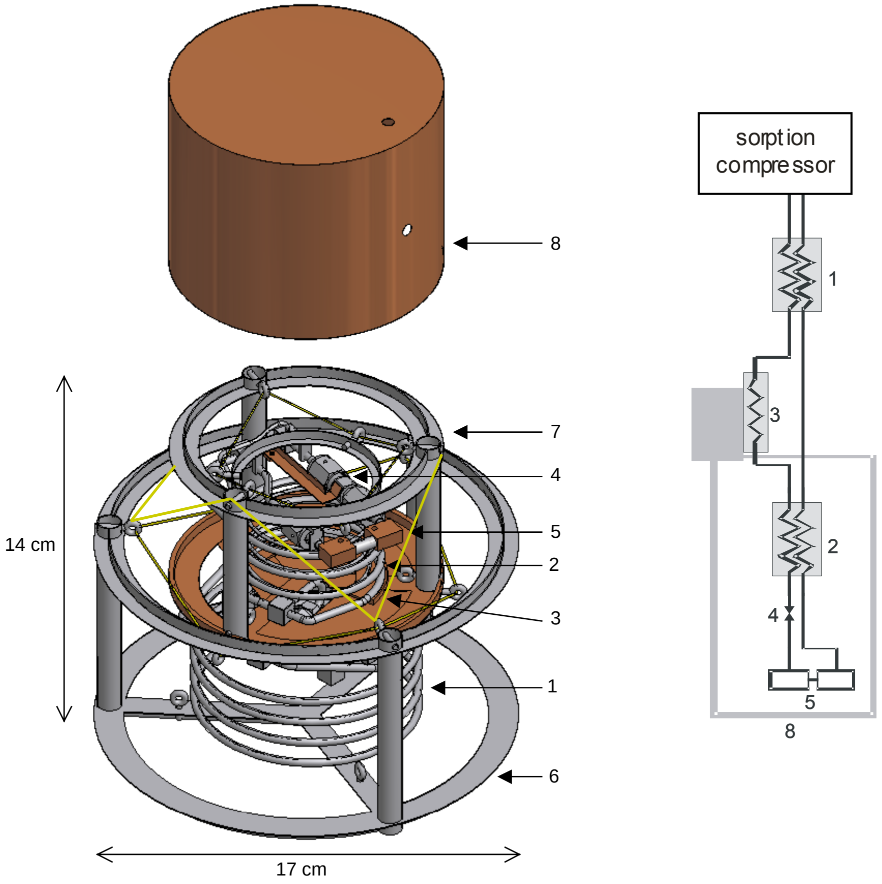


Figure 5. Design of the cold stage. The numbers correspond to the following parts: 1) 1st counterflow heat exchanger; 2) 2nd counterflow heat exchanger; 3) 14.5 K pre-cooler; 4) JT flow restriction; 5) evaporator; 6) 50 K support structure; 7) 14.5 K support structure; 8) 14.5 K radiation shield.

power is made available as net cooling, and the required gross cooling power can be kept at a minimum (and associated with the required radiator area). Table 2 lists the calculated losses of the cold stage. These very small losses are achieved by: 1) using a radiation shield at 14.5 K and 2) using a Kevlar cable construction. Without using these two measures, the thermal losses would be several milliwatts. The mechanical design of the cold stage is engineered to withstand the launch loads.

The fluidic interface to the low and high pressure lines of the cold stage is accomplished via two 1/8” VCR connections (at the bottom of the cold stage, not visible in the picture). Thermal and mechanical interfaces to the cold stage exist at the bottom of the 50 K supporting structure and at the bottom of the 14.5 K supporting structure. In stationary operation, virtually no heat flows will be present via the mechanical interface at 50 K, and a very small heat flow to the 14.5 K interface. In the integrated design of the helium/hydrogen sorption cooler architecture as described above, the hydrogen cold stage will be integrated with the helium cold stage so that no external 14.5 K precooling facility is required.

The thermal-mechanical interface of the thermal load to the evaporator at 4.5 K has an area of approximately 1 cm^2; this area can easily be adapted in the design, if necessary.

Control system

The data acquisition and control system of the 4 K sorption cooler contains the following components:

1. Power supplies for the different sensors in the system, as well as for the heaters that are located in the system;
2. A data acquisition system to sense the electrical signals from all sensors and from the currents and voltages that make up the heater powers;
3. A computing system to calculate the required output (heater) signals that are needed to control the cooler, and (if necessary) to display and/or store the measured data;
4. Analog and digital output circuitry to power the different heaters in the system.

Although a careful design of this system is important, a real technology development was not required – in contrast to the other cooler components. In an early phase of the project we, therefore, agreed with ESA to use a PC-based standard National Instruments data-acquisition system to control the cooler. This is a flexible, powerful and yet cost-effective solution. For a future flight cooler, a compact stand-alone controller can be designed which performs the same functions. A software algorithm is used to control the sorption cooler; a similar software algorithm will also be required for a future flight version of the cooler.

TEST SET-UP WITH THE DEVELOPED COOLER

This section describes the test set-up with the breadboard 4K sorption cooler. In the test set-up, the operating conditions must correspond to space operation, following the system design described above. This means that the set-up must contain the following components:

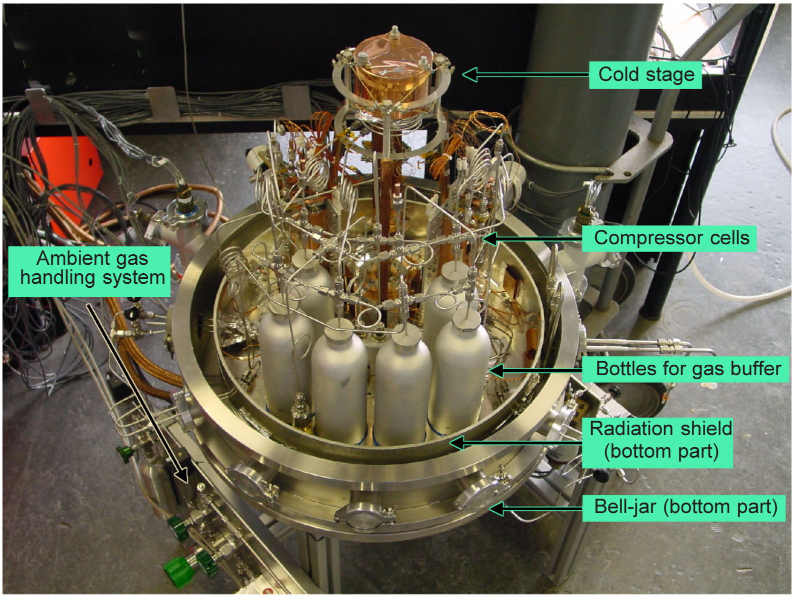
1. A large vacuum bell-jar.
2. A mechanical precooler that can provide the temperature levels of 50 K for the sorption compressor cells and 14.5 K for the precooling of the cold stage.
3. A thermal radiation shield around all components of the sorption cooler, to prevent 300 K radiation from reaching the cooler components.
4. A helium gas handling system outside the bell-jar, which is connected to the sorption cooler inside the bell-jar. This gas handling system is required to pump down the sorption cooler and clean it from contaminant gases, and to fill it with helium gas.

Photographs of the set-up are given in Fig. 6 and Fig. 7, with explanation of the different parts given in the photographs and in the captions.

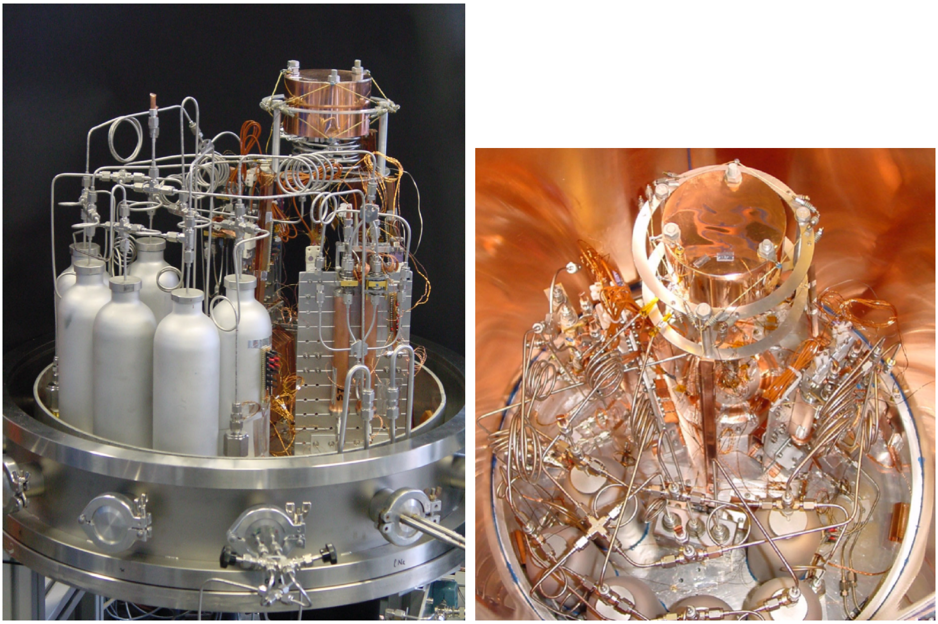
PERFORMANCE TESTS

A number of different performance tests have been carried out on the 4.5 K sorption cooler; important results are summarized in Table 3. More extensive test results will be described elsewhere. From the tests, it appeared that the sorption cooler performs very much as it was expected.

One of the check valves of one sorption cell in the first compressor stage was not performing properly, so it was decided not to use this sorption cell and to operate the cooler with three sorption cells: one in the first stage and two in the second stage. The resulting cycle time of the cel in the first stage was about 5 minutes and about 16 minutes for the two cells in the second stage. It appeared that the cooler could be operated very well with three cells, and in this way the redundancy of the sorption compressor architecture was demonstrated.



(a) 4K sorption cooler inside the bottom part of the bell-jar. The cooler components are mounted on the bottom part of the radiation shield; this bottom part is thermally linked to the first stage of a powerful two-stage GM cooler.



(b) Side-view of 4K sorption cooler. (c) Top view of cooler inside 50 K radiation shield.

Figure 6. Photographs of the test set-up.

The cold-end temperature was controlled to 4.5 K exactly, with a fluctuation of about +/- 1 mK. This fluctuation is determined by the accuracy of the temperature controller, a Lakeshore 331 which has a resolution of 1 mK.[6] Furthermore, the cold end has a very small thermal mass, approximately 5 gram of copper. The temperature stability can be reduced to well

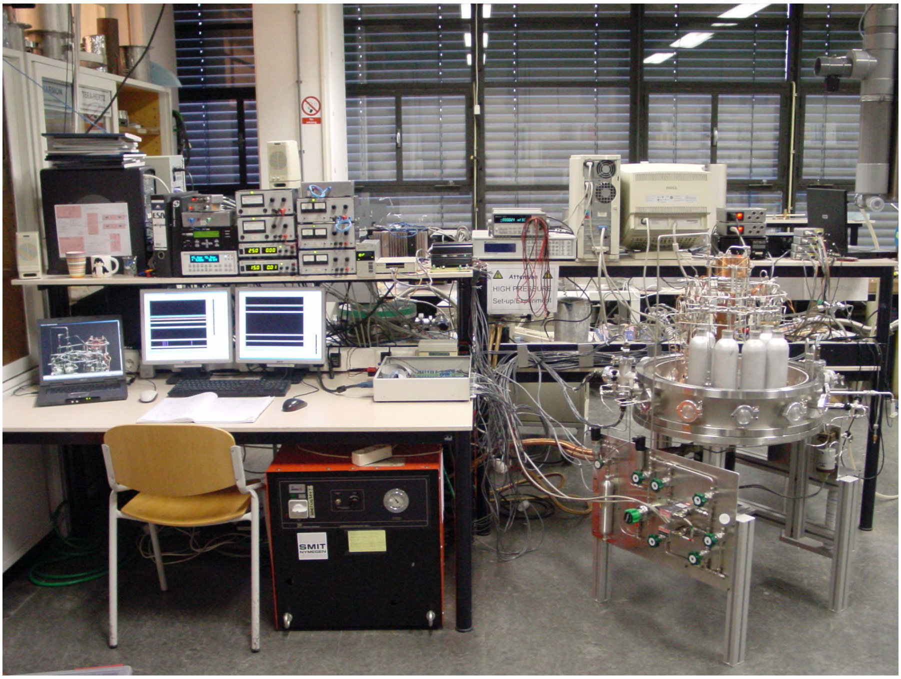


Figure 7. Photograph of the total system.

below 1 mK if the thermal mass connected to the evaporator is increased and if a faster and more accurate temperature controller is used. The temperature fluctuation of the *uncontrolled* cold end is about 10 mK; in this case the temperature fluctuates with the low-pressure in the evaporators.

The resulting total input power is 1.96 W and the corresponding radiator area is 7.9 m^2 as shown in Table 3. This is close to the predicted value of 8.3 m^2, and well within the specified area of 9.1 m^2 (which follows from the specified maximum input power of 2.5 W at 50 K).

Table 3. Summary of the required and measured performances.

Requirement	*Measured*
Cooling capacity > 5 mW at 4.5 K	4.5 mW at 4.5 K
Temperature stability: < 1 mK for a period of 1 hour < 10 mK for 2 weeks < 0.1 K over cooler lifetime	 1 mK for 1 hour (controlled), < 4 mK for two weeks (uncontrolled)
Exported vibrations < 1 μN/√Hz	<< 1 μN/√Hz (analyzed)
Power consumption < 200 W	1.96 W (without electronics)
Lifetime > 5 years	expected, not measured
Cooler operable continuously during its lifetime	2.5 months tested with 17 days of uninterrupted operation
Cooler capable of 20 start-stop cycles (only compr. cells pressure build-up)	> 20 start-stop cycles
Cooler able to operate under any orientation	horizontal and tilted 45 degrees
Cold radiator (T = 40 – 80 K), maximum cooling power 2.5 W at 50 K or 9.1 m^2 radiator area	0.891 W @ 47 K + 1.065 W @ 50 K or 4.2 m^2 + 3.7 m^2 = 7.9 m^2
Cooler mass < 10 kg	8.3 kg (excl. platforms)
Designed to maximise Coefficient of Performance	OK

CONCLUSIONS

From the test results it can be concluded that the developed 4.5 K helium sorption cooler is able to cool to 4.5 K and supply vibration-free cooling. The measured cooler performance is summarized in Table 3, which also contains the corresponding requirements for the cooler given by ESA. It can be concluded that virtually all performance numbers fit within the limit values that were specified by ESA. In addition, the measured cooler behavior corresponds very well to our modeled and predicted behavior, which was presented in earlier phases of this project. This validates our basic understanding and the (dynamic) models underlying this technology.

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