Sorption-based vibration-free cooler for the METIS instrument on E-ELT

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ABSTRACT

METIS is the 'Mid-infrared ELT Imager and Spectrograph' for the European Extremely Large Telescope. This E-ELT instrument will cover the thermal/mid-infrared wavelength range from 3 to 14 μm and will require cryogenic cooling of detectors and optics. We present a vibration-free cooling technology for this instrument based on sorption coolers developed at the University of Twente in collaboration with Dutch Space. In the baseline design, the instrument has four temperature levels: N-band: detector at 8 K and optics at 25 K; L/M-band: detector at 40K and optics at 77 K. The latter temperature is established by a liquid nitrogen supply with adequate cooling power. The cooling powers required at the lower three levels are 0.4 W, 1.1 W, and 1.4 W, respectively. The cryogenic cooling technology that we propose uses a compressor based on the cyclic adsorption and desorption of a working gas on a sorber material such as activated carbon. Under desorption, a high pressure can be established. When expanding the high-pressure fluid over a flow restriction, cooling is obtained. The big advantage of this cooling technology is that, apart from passive valves, it contains no moving parts and, therefore, generates no vibrations. This, obviously, is highly attractive in sensitive, high-performance optical systems. A further advantage is the high temperature stability down to the mK level. In a Dutch national research program we aim to develop a cooler demonstrator for METIS. In the paper we will describe our cooler technology and discuss the developments towards the METIS cooler demonstrator.

Keywords: vibration-free, cooler, infrared, sorption, METIS, demonstrator, E-ELT
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1. INTRODUCTION

The E-ELT with its 42m aperture will enhance observations in terrestrial optical/infrared astronomy. Apart from increased sensitivity with respect to VLT, E-ELT will also enable observation in the thermal and mid-IR range of 2.5μm and beyond. The 'Mid-infrared ELT Imager and Spectrograph' (METIS) is the E-ELT instrument to cover the thermal/mid-infrared wavelength range from 3 – 14 μm. The METIS instrument is discussed more extensively in another contribution to this conference[1]. METIS consist of a warm part including instrumentation, structural supports and a vacuum vessel in ambient and a cold part inside the vacuum vessel, consisting of the cold optics and detectors, see Figure 1.

The present paper describes a cryogenic system for METIS based on sorption cooling. Sorption cooling is a technology that gives flexibility in the integration with the instrument and that does not produce any disturbances that might influence instrument performance. The study focuses on the dimensioning of the sorption cooling system and on the accommodation of the cooler components in the METIS design.

METIS cooling requirements

The temperature levels of the imaging, dispersing and detecting subsystems of the instrument determine METIS' radiometric performance. The detectors require a temperature level of 40 K for the L/M band and of 8 K for the N band. The temperatures of the optics, opto-mechanical components, and the thermal radiation shield are driven by their contribution to the overall noise budget. Their contribution to the noise budget shall be lower than contributions from the telescope and from the atmosphere. Furthermore, in configuration trade-offs the number of different temperature levels has been reduced to four, see Table 1.

Ground-based and Airborne Instrumentation for Astronomy IV, edited by Ian S. McLean, Suzanne K. Ramsay, Hideki Takami, Proc. of SPIE Vol. 8446, 84467O · © 2012 SPIE · CCC code: 0277-786X/12/$18 · doi: 10.1117/12.927002

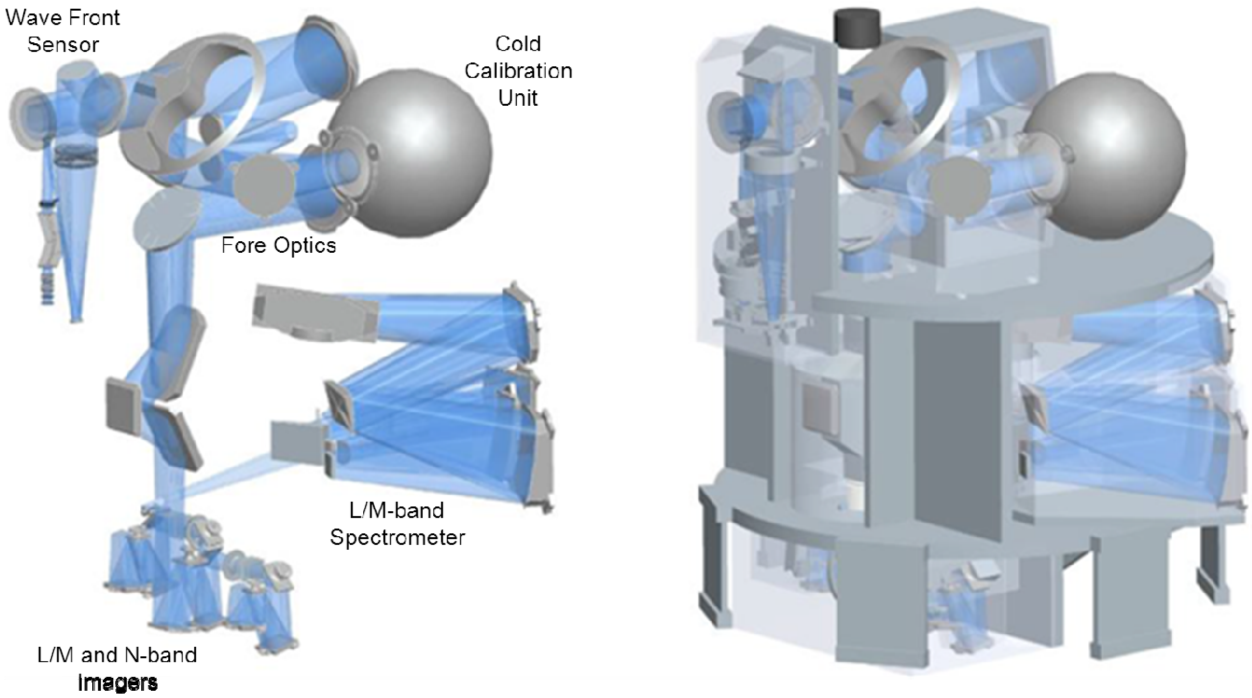


Figure 1. Impression of the METIS optical system on the left and its integration with the main instrument structure on the right. The instrument as a whole is surrounded by a thermal radiation shield and is accommodated in a spherical vacuum vessel with a diameter of 2.5 m. *(Diagrams taken from the METIS Phase A study reporting.)*

Table 1: Required temperature levels of METIS imaging, dispersive and detection units.

METIS unit	Required max temperature (K)
Radiation shield	85
Fore Optics	85
Cold Calibration Unit	85
Wave Front Sensor	85
LM-Imager	85
LM-Spectrometer	85
LM-Band Detectors	40
N-Band Imager	25
N-Band Detectors	8

The 85 K units will be thermally linked to the liquid-nitrogen thermal bus. Each of the three lower temperature levels is served by a sorption cooler stage. Table 2 shows the respective heat loads at these cryogenic interface levels, designated I, II and III.

Table 2: Heat loads at the colder interfaces.

Cryogenic interface	Temperature (K)	Heat load (W)
I	40	1.4
II	25	1.1
III	8	0.4

Other requirements

A key factor in the design of METIS is limiting the level of vibrations introduced at the detectors by the cooling system. Conventional cooling solutions such as Stirling or even pulse-tube coolers require dedicated design measures with associated extra costs and risks to reduce or eliminate the vibrations at the detector level. Failure to properly reduce vibrations can lead to a significant reduction in the optical performance of the instrument.

Equally important is the short-term temperature stability of the cooling system at the cryogenic interfaces to prevent calibration errors due to changing detector temperatures.

Reliability is directly linked to the availability of the instrument. Apart from a few passive valves, sorption-based coolers have no moving parts, and thus reliability is expected to be excellent.

2. SORPTION-COOLER BASICS

A sorption compressor is a thermal 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 well-controlled way cooling can be obtained.

A schematic of a cooler operating with a sorption compressor is shown in Figure 2. The activated carbon is placed in a compressor container (1) that is thermally separated from a heat sink (5) by means of a gas gap (3). The gas-gap actuator (2) holds a small amount of carbon filled with a contact gas that is specifically selected for the working conditions of the cooler (e.g. hydrogen). By heating the carbon of the actuator, this contact gas is desorbed and fills the gap, thus establishing a good thermal contact between the container and the heat sink. The activated carbon in the container cools down to the heat-sink temperature and adsorbs gas until the pressure in the container is below that of the low-pressure buffer (8). At that point, the low-pressure valve (7) opens and gas from the low-pressure buffer flows into the container and is adsorbed onto the carbon. When the carbon in the compressor container is saturated with the working gas, then the heating of the gas-gap actuator is stopped. The carbon in the gas-gap actuator cools and as a result, the contact gas in the gap is re-adsorbed and the compressor container becomes thermally insulated from the heat sink. Next, the carbon in the container is heated by an internal heater (4) so that the working gas is desorbed and a pressure is built up in the container. As soon as the pressure in the container is above that of the high-pressure buffer (10), the high-pressure valve (9) opens and high-pressure gas flows from the container to the high-pressure buffer passing the aftercooler (6). From this buffer, the gas flows through a counterflow heat exchanger (13) and through a flow restriction (11) where it expands and thus cools due to the Joule-Thomson effect[2]. The working gas liquefies and is assembled in an evaporator (12). This is the actual cooler tip where cooling power is available. Heat from the environment is absorbed in the evaporation of the liquid. The evaporated working fluid returns to the low-pressure buffer via the counterflow heat exchanger. In passing the heat exchanger, it takes up heat from the incoming high-pressure gas that thus is precooled on its way to the restriction. By cyclic heating and cooling of the container, a more or less continuous gas flow through the restriction can be established and maintained. In case of relatively high desired pressure ratios, the efficiency of the cooler is usually increased by applying two sorption-compressor stages in series. Also, an additional pre-cooler can be applied to precool the high-pressure gas before it enters the counterflow heat exchanger, thus further increasing the cooler efficiency.

Apart from the passive valves, sorption coolers have no moving parts, which is attractive for a number of reasons; Firstly, wear is not an issue and, therefore, extremely long life can be expected. Secondly, in contrast to mechanical piston compressors, no vibrations are generated, relevant to e.g. vibration-sensitive devices such as optical detectors. Finally, the absence of moving parts permits scaling of the cooler to small size, which is especially of interest because the efficiency of the cooler is fundamentally independent of its size. Also, cold tip and sorption compressor may be well separated, providing substantial flexibility in accommodation and instrument design. Furthermore, since no electric motor drive is used, Electro-Magnetic Interference (EMI) is far less an issue as compared to standard mechanical coolers.

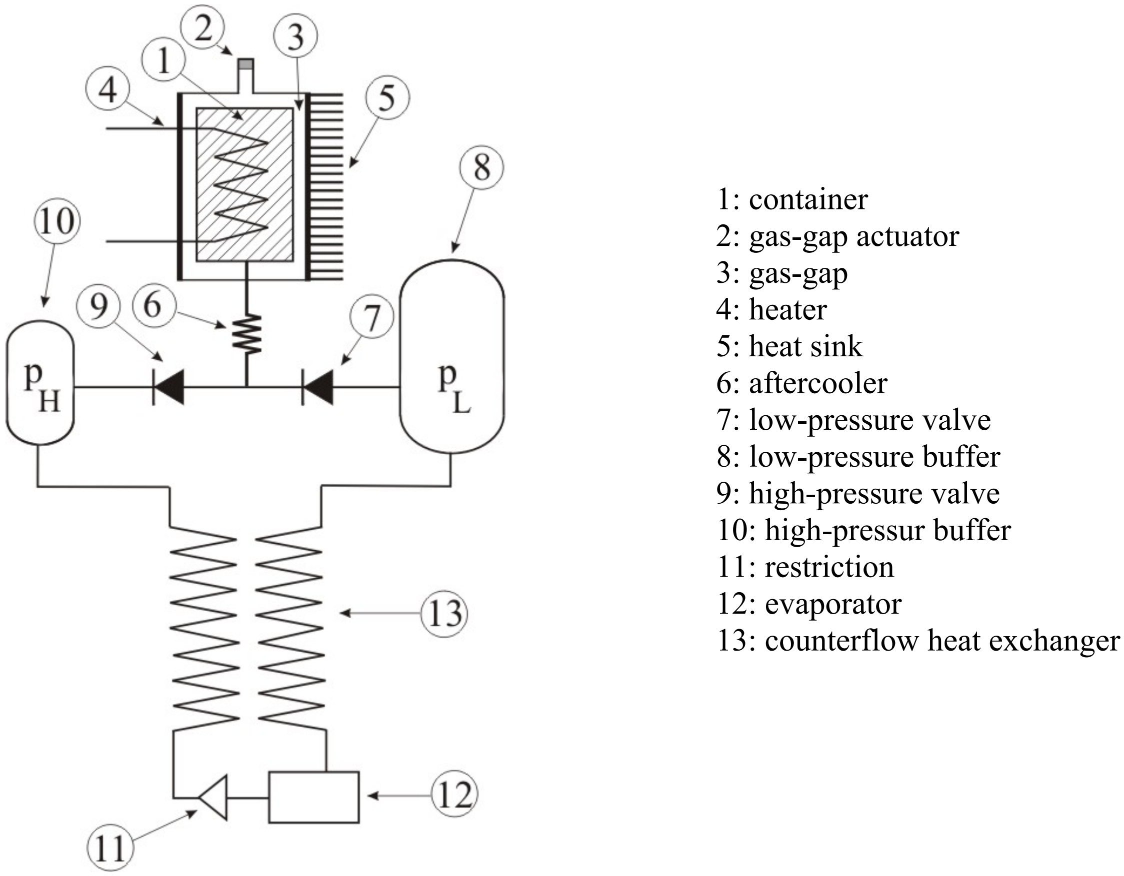
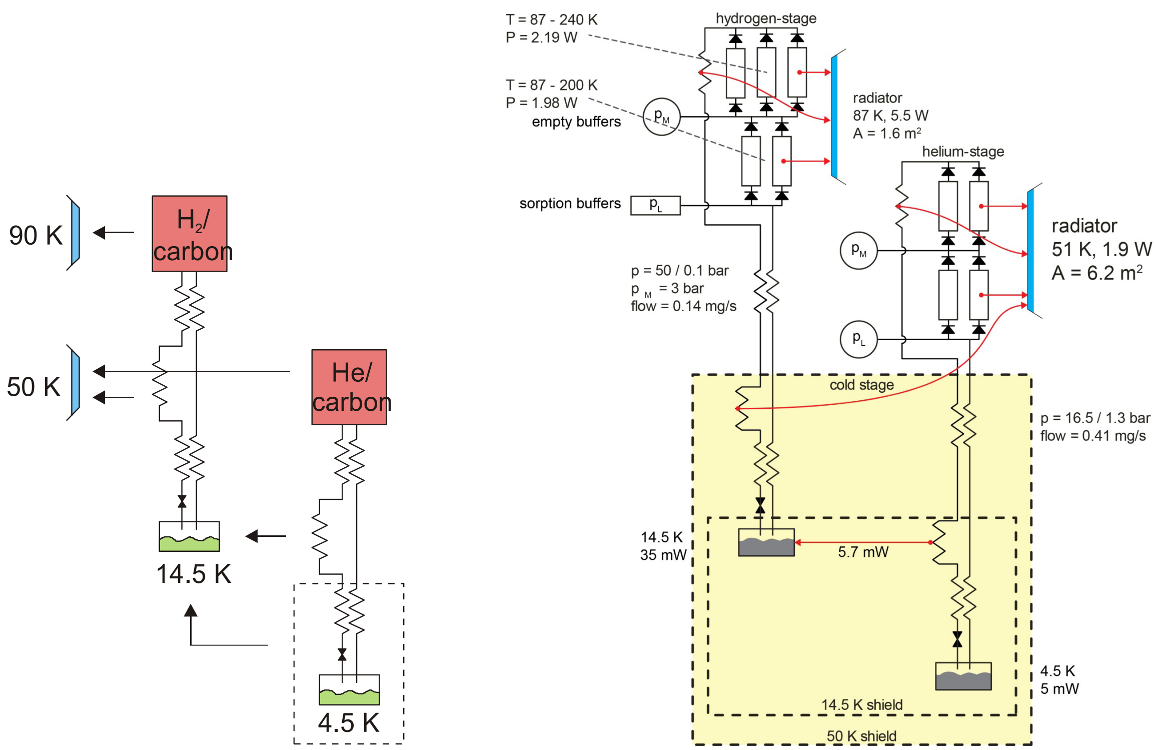


Figure 2. Schematic representation of a cooler with sorption compressor.

3. SORPTION COOLERS FOR SCIENTIFIC SPACE MISSIONS

Because of the absence of moving parts and the resulting extremely low level of vibrations, sorption-based coolers are very attractive for cooling optical detectors in future space missions. Recognizing this potential, ESA awarded the University of Twente a project in the Technology Research Programme to develop a sorption cooler targeted for the Darwin mission. In our design that is schematically depicted in Figure 3, a cooler-tip temperature of 4.5 K is established in two steps[3,4]. 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 is able to reach 4.5 K with a cooling power of 5 mW. Both coolers have two-stage compressors, the helium compressor with two times two compressor cells, and the hydrogen with two and three cells. The hydrogen compressor is thermally linked to a 87 K radiator heat sink, whereas the helium-stage compressor is heat sunk at a 51 K radiator. This 51K radiator also precools the hydrogen gas. In the ESA-TRP project the helium stage was realized and successfully tested with a temperature stability of 1 mK for 1 hour and 4 mK for a period of two weeks[4]. Figure 4 shows a photograph of the 4.5 K cooler demonstrator setup. In this on-ground test setup the heat-sink temperature levels of 14.5 K and 51 K were realized with a two-stage mechanical cooler available in the lab.



(a) (b)

Figure 3. (a) Schematic picture of the proposed helium / hydrogen sorption cooler, which is precooled by two passive radiators at about 50 K and 87 K. (b) Detailed schematic of the helium and hydrogen sorption coolers.

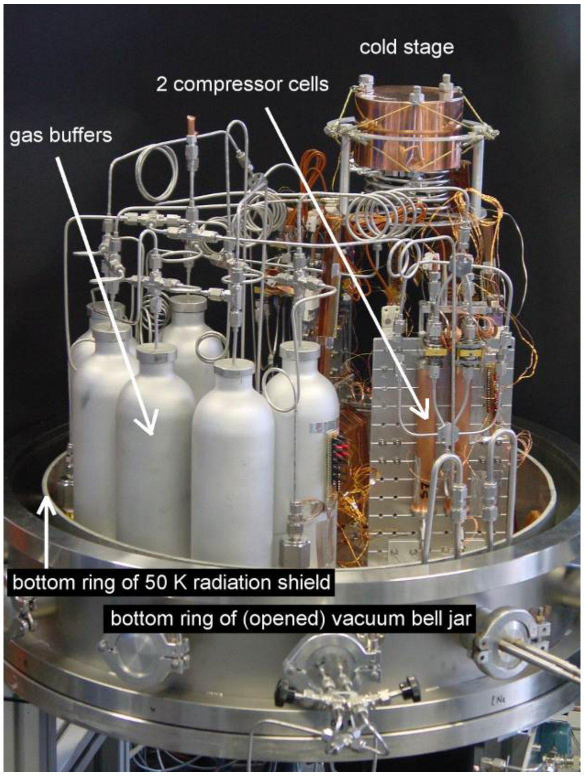


Figure 4. Photograph of the test set-up with the 4.5 K sorption cooler.

In a follow-up ESA project we developed the hydrogen-stage of the Darwin cooler configuration. Apart from precooling the helium stage, the hydrogen-stage cooler provides an additional cooling power of 35 mW at 14.5 K as shown in Figure 3. The sorption compressor cells pump the hydrogen gas from a low pressure of only 0.1 bar to a medium pressure at 3 bar, and subsequently to the high-pressure side of the cold stage at 50 bar. Currently, the hydrogen-stage cooler is being assembled and test readiness is expected in summer 2012. A specific extra feature in the hydrogen-stage compressor is the chemical getter that is required to pump hydrogen gas that has diffused into the gap space through the container wall. Figure 5 shows a compressor cell prior to assembly in the setup.

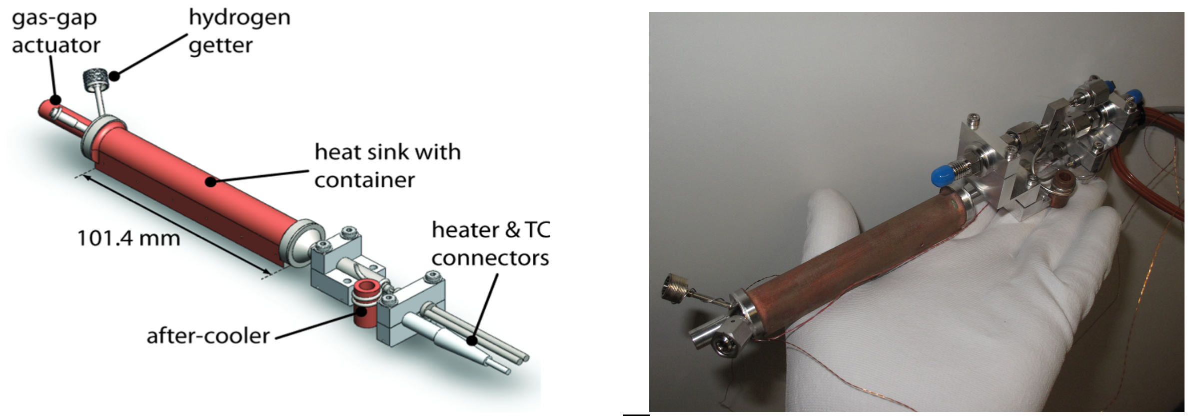


Figure 5. Sorption-compressor cell of the 14.5 K hydrogen-stage cooler: left: design drawing; right: photograph of cell prior to assembly in the test setup.

4. SORPTION COOLER FOR METIS

4.1 Introduction

Based on our experience with sorption-based cooling, we designed a sorption Joule-Thomson cooler that can meet the requirements of the METIS instrument as discussed in section 2. Our baseline design is a three-stage cooler consisting of a neon stage, a hydrogen stage and a helium stage. This section discusses the design of this METIS sorption cooler with specific attention to the neon-based 40 K cooler.

4.2 Compressor design and adsorbent material

In our METIS cooler design the cells are cylindrical with axially inserted heaters. Both the container of the cell and the heater are parasitic heat capacities and their masses have been minimized. The containers are made of SS316L and the thickness of their walls depends on the diameter of the cell and the maximum pressure and temperature. In our baseline design the cells have a diameter of 2 cm and are 50 cm in length. There are multiple reasons for this choice, including relative ease of fabrication and the scaling of the cooler chain size as a function of cell's dimensions. The adsorbent used is Saran carbon. This type of carbon is well studied and the University of Twente has successfully built coolers based on this material as the compressor adsorbent. The amount of adsorbed gas is a function of both temperature and pressure. Generally, the lower the temperature and the higher the pressure, the more gas is adsorbed. Sorption compressors utilize this principle by adsorbing some significant amount of working gas at low temperature and releasing it at much higher pressure after heating up the adsorbent.

4.3 Gas-gap heat switch

As discussed in section 2, a gas-gap heat switch is a part of a compressor cell design (see Figure 2). It is used for reversible switching of the thermal resistance between the sorption cell and the heat sink. The switching is accomplished by cycling the pressure in the gas-gap between the high continuum-flow limit when a sorption cell cools down and a low value in the molecular-flow range when the cell is heated up, see Figure 6. In this way substantial power savings can be accomplished because there is very limited heat transfer from the cell to the sink when the cell is hot. At the same time, the cool-down can be relatively fast, depending on the gas-gap fluid used and the width of the gap. To increase the pressure in the gas gap, a small piece of adsorbent (i.e. the gas-gap actuator) is actively heated, causing the gas stored within its body to desorb. Switching off the heating initiates passive cooling of the adsorbent, resulting in the re-adsorption of the gas and decrease of the pressure inside the gas gap. The functioning of the gas gap greatly affects the performance of the compressor. The parasitic conduction through the gas gap in the low-pressure OFF state generates heat losses. On the other hand the maximum achievable conductivity in the ON state determines the cool-down time and thus the number of cells in the compressor. In our design we use a gas gap of 500 μm in width, operating with nitrogen gas.

4.4 Loss budget and margins

In the thermodynamic modeling of the coolers the heat capacities of the compressor cells, the heaters and adsorbent materials were taken into account. Additional loss factors were accounted for by including relatively large margins in the design:

- The void volume of the compressor cells was increased by 2 cm^3 per meter length of the cell (in our baseline of 50 cm, therefore, 1 cm^3 margin was added to the dead volume);
- A temperature difference of 3 K was assumed between the low operating temperature of a compressor cell and the heat-sink temperature;
- The required cooling powers were increased by 25% at each of the stages,
- The required pre-cooling powers were also increased by 25 %,
- The worst-case duration of the compression cycle was used in the calculations,
- On top of the already mentioned margins, the resulting input power was increased by a further 10 %.

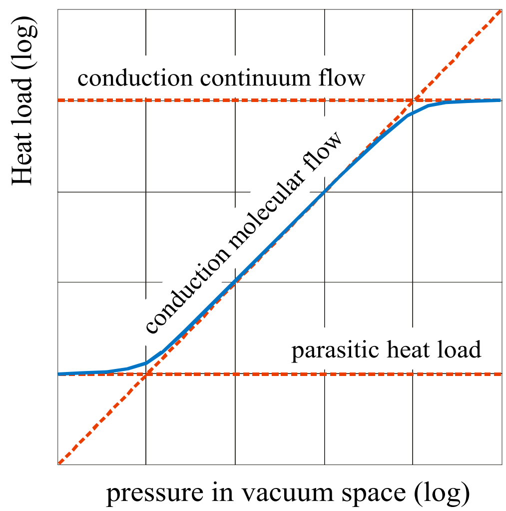


Figure 6. Schematic representation of the heat flow through a gas-gap heat switch. At very low pressures in the molecular-flow regime, the mean fee path of the gas molecules is much smaller than the gap size. The smallest heat flow achievable is determined by parasitic heat load arising from radiation and conduction through support structures. At higher pressures the mean free path decreases and once below the gap size, the heat flow enters the continuum regime. Here, the heat flow is inversely proportional to the gap size.

4.5 METIS sorption cooler system design

As mentioned before, the METIS cooler consists of three separate cooler stages, each providing a different cooling temperature. The overall cooler chain design is shown in Figure 7.

A helium cooler is used to obtain the 8K level with a cooling power of 0.4 W (where the design is based on 0.5 W, see margins listed above. Because of the relatively low pressure ratio, the helium compressor can be a single-stage compressor. Three different pre-cooling temperatures are used in the cold stage at 40K, 25K and 15K to facilitate the maximum achievable performance. Because the cooling temperature is above the critical temperature of helium (8K vs. 5.19K) the gas will not liquefy during expansion.

The 25K temperature level is provided by a hydrogen cooler. It operates with a two-stage compressor and the cold stage facilitates double JT expansion: the first to reach 25K, required both by the METIS instrument (1.1 W) and for pre-cooling the helium stage, and the second to produce a 15K solely for the purpose of the helium cooler pre-cooling.

Finally, a neon-operated cooler delivers the required cooling power at 40K (1.4 W). This cooler uses a single-stage compressor and its cooling capacity is split into cooling of the METIS instrument and pre-cooling of the helium and hydrogen-stage coolers.

In the optimization process of the whole cooler chain first the helium cooler was optimized and as a result the input power and the required pre-cooling powers were obtained, as well as the helium compressor mass. After adding the design margins, the required pre-cooling powers at 15K and 25K were added to the loads in the optimization of the hydrogen cooler. The optimization of the hydrogen cooler followed and finally the neon stage was calculated using the METIS 40K requirements and the pre-cooling needs of the helium and hydrogen coolers as inputs.

As can be derived from Figure 7, a total of 1.5 kW is needed as input power that is dumped at the liquid-nitrogen cryogenic bus. In total 199 compressor cells are needed of which by far most are needed in the helium-stage cooler (173). The total amount of carbon needed is somewhat more than 34 kg of which about 30 kg in the helium stage. Including all other materials, the total cooler mass will be a few hundred kg, strongly depending on cooler lay-out and scaling with the required cooling performance.

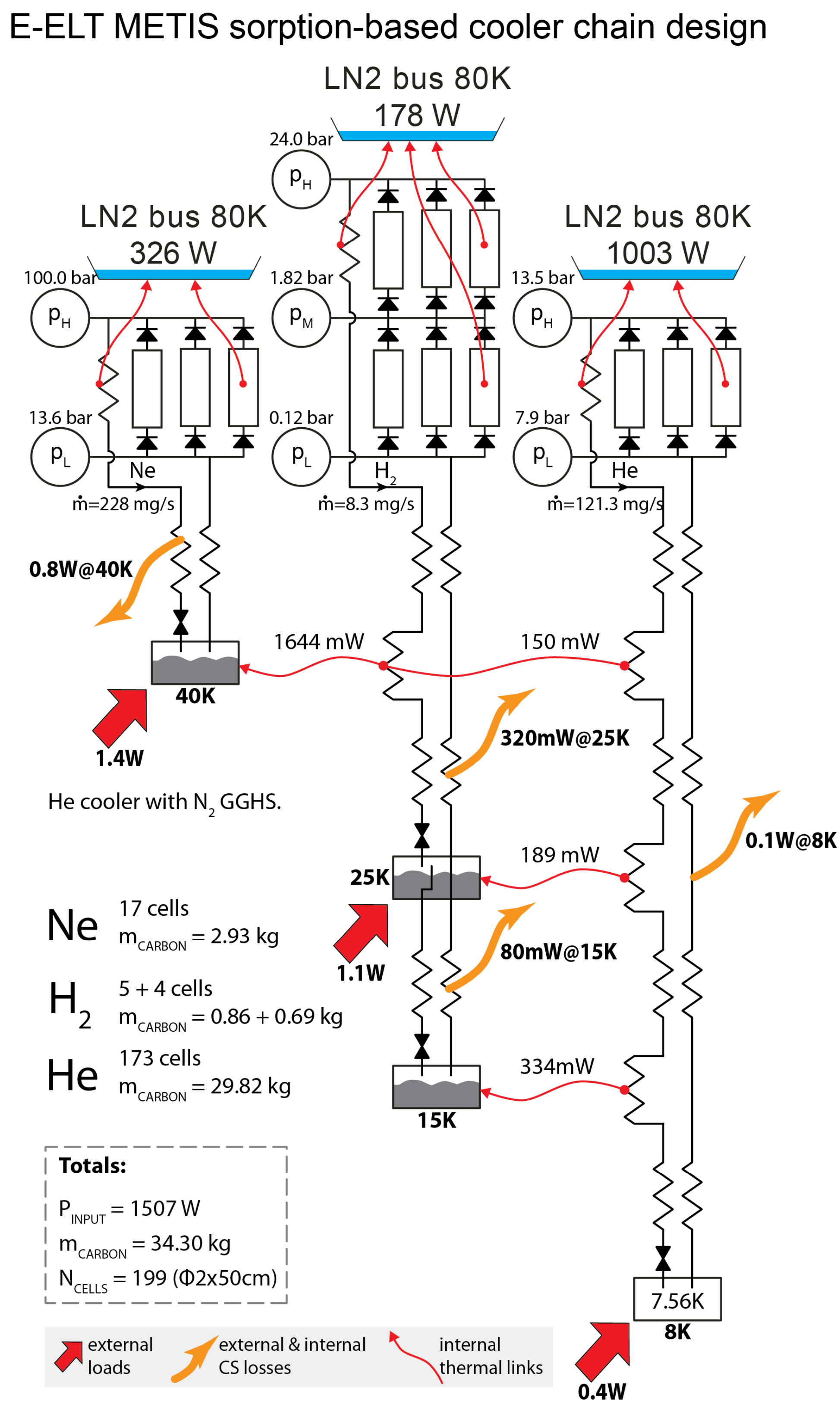


Figure 7. Schematic of the METIS sorption-cooler baseline design.

4.6 40 K neon-stage sorption cooler

A more detailed design is already made of the 40K neon-stage cooler. It will be realized as a demonstrator comparable to the neon-stage cooler in the METIS cooling chain. It will be 60x40x15 cm in size and will deliver more than 1 W of continuous cooling power. Its modular, redundant construction allows for further, effortless scale-up to higher cooling powers. This cooler will need 100 W of input power corresponding to 2.2 l/h of liquid nitrogen. An impression of the 40 K sorption cooler is given in Figure 8.

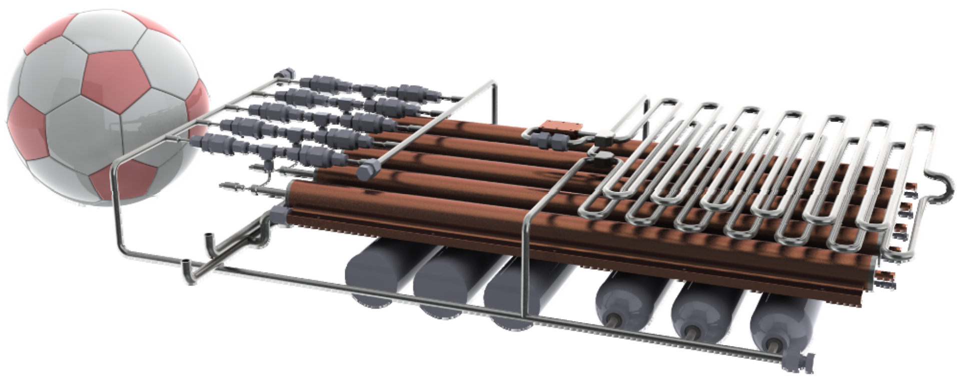


Figure 8. Impression of the neon-based sorption cooler with a cooling power of 1 W at 40 K. In the center on the top is the 40 K cold plate with close to it the Joule-Thomson restriction, and to the right the counter-flow heat exchanger. At the bottom are the buffers, and in between the buffers and the cold plate are the compressor cells. On the top left are the check valves connecting the compressor to the cold stage.

5. FUTURE DEVELOPMENTS

The priority of further developments on the sorption cooling system for METIS is based on an assessment of the maturity level of the various components. Currently an assessment is being undertaken under national funding to define the steps necessary for the design, development and verification of a sorption cooling system for the METIS instrument.

The following list of relevant aspects which require further development have so far been identified:

- With respect to the currently available helium sorption coolers, the adsorption temperature of the METIS helium stage is significantly higher.
- The METIS neon stage performance is currently based on measured neon sorption isotherms. This performance needs to be verified in representative sorption cells.
- The cooling powers that METIS requires are higher than the currently operating sorption coolers typically deliver. One of the good features of the existing sorption coolers is that they are based on sets of standard sorption cells. If the cooling power demand increases, more cells can be added. For METIS, the cooling powers are such that with the current standard sorption cell size this would lead to large numbers of sorption cells in parallel. Therefore a trade-off is planned to determine the optimum sorption cell size for the METIS application.
- Due to the higher cooling powers, the required mass flows will be significantly higher than in the sorption coolers made so far. Therefore, the design of the heat exchangers is currently revisited in order to reduce the required size.

Currently the development and test of three major demonstrator models is envisioned with the aim of validating solutions to the identified issues.

- Ne demonstrator: A neon-based sorption cooler which is representative of the neon stage envisioned for METIS in terms of temperature levels and heat loads will be developed and tested in parallel to a PhD project conducted by the University of Twente. The aim is to validate the neon stage performance. This demonstrator is planned for completion in 2013.
- Scaled He compressor: A scaled-down version of the METIS helium compressor stage will be developed and tested by the University of Twente and Dutch Space. The demonstrator will contain sorption cells of sizes representative for METIS and will operate with the adsorption temperature of METIS. However, the number of sorption cells is limited to 10% of the METIS helium compressor stage. The aim is to validate the performance of a scaled-down METIS He compressor, in particular regarding cell sizes and adsorption temperature. This demonstrator is planned for completion in 2015.
- He cold stage: A cold stage for the helium-based sorption cooler will be will be developed and tested in parallel to the helium compressor development by the University of Twente and Dutch Space. The cold stage will be representative of METIS in terms of heat loads, mass flows and temperature levels, but will operate using a conventional compressor. Precooling will be performed by conventional mechanical coolers. The aim is to validate the cold stage performance, in particular regarding the heat exchangers. This demonstrator is planned for completion in 2015.

ACKNOWLEDGMENTS

This research is enabled through the Netherlands Research School for Astronomy (NOVA) by financial support from the Netherlands Organization for Scientific Research (NWO) under contract 184.021.006. The authors are indebted to Bernhard Brandl of Leiden University and to Lars Venema and Ronald Roelfsema of the Dutch Institute for Radio Astronomy (ASTRON) for their stimulating contributions and valuable inputs in the discussions on METIS. Furthermore, Johannes Burger of COOLL Sustainable Energy Solutions is acknowledged for his earlier work on the ESA 4.5 K sorption cooler, and his continuing support in discussions.

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