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 (E-ELT). This E-ELT instrument will cover the thermal/mid-infrared wavelength range from 3 μm to14 μm and requires 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 40 K 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 is based on the cyclic adsorption and desorption of a working gas on an adsorbent 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 it contains no activated moving parts and, therefore, generates no vibrations. This 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 demonstrator version for METIS. In the paper we will describe our cooler technology and discuss the developments towards the METIS cooler demonstrator.

INTRODUCTION

Considered worldwide as one of the highest priorities in ground-based astronomy, extremely large telescopes will vastly advance astrophysical knowledge and allow for detailed observations of among others the first objects in the universe and planets in other star systems. The revolutionary new ground-based telescope concept, the European Extremely Large Telescope (E-ELT)[1], will have a 40-meter-class main mirror and will be the largest optical/infrared telescope in the world. Apart from increased sensitivity with respect to VLT, E-ELT will also enable observation in the thermal and mid-IR range of 2.5 μm and beyond. The 'Mid-infrared ELT Imager and Spectrograph' (METIS) is one of eight proposed instruments for E-ELT, and will offer imaging and spectroscopy over the wavelength range of 3-14 microns, covering the L, M and N bands[2]. METIS consists of a warm part that includes instrumentation, structural supports and a vacuum chamber at ambient temperature and a cold part inside the vacuum chamber that contains the cold optics and detectors, shown in Fig. 1.

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Sorption-based cooling has been under development at the University of Twente for over 10 years[3-5]. This technology offers vibration-free, long-life operation with minimum maintenance. It also gives flexibility in the integration with the instrument. In this paper, a cryogenic system for METIS based on sorption cooling is described. 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 of 40 K for the L/M band and of 8 K for the N band. The instrument and radiation shield temperatures are determined by the requirement of background limited observations. Table 1 shows the temperature levels for METIS units.

All of the 85 K units, except the radiation shield, will be thermally attached to a backbone which is cooled by a liquid nitrogen (LN2) bus. Another LN2 bus will be set for the radiation shield. Each of the three lower temperature levels, i.e. 40 K, 25 K and 8 K, will be provided by a sorption cooler stage. The respective heat loads at these lower temperature levels are also shown in Table 1. The sorption cooler system uses a heat sink at 70 K, served by a separate LN2 loop.

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

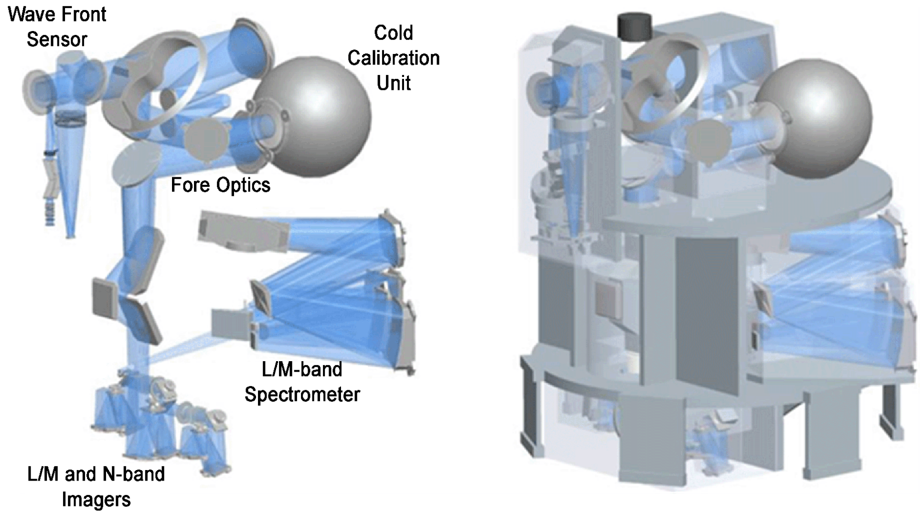

Figure 1. Impression of the METIS optical system on the left and its integration with the main instrument structure on the right. The instrument as a whole is surrounded by a thermal radiation shield and is accommodated in a spherical vacuum chamber with a diameter of 2.5 m.

Table 1. Required temperature levels and heat loads of METIS cryogenic units

METIS unit	Required max temperature (K)	Heat load (W)
Radiation Shield	85	-
Fore Optics	85	
Cold Calibration Unit	85	
Wave Front Sensor	85	
LM-Imager	85	
LM-Spectrometer	85	
LM-Band Detectors	40	1.4
N-Band Imager	25	1.1
N-Band Detectors	8	0.4

coolers require dedicated design measures with associated extra costs and risks to reduce or eliminate the vibrations at the detector. 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.

METIS SORPTION COOLER CHAIN DESIGN

The METIS cooler consists of three separate stages arranged in parallel, each providing a different cooling temperature. The overall cooler chain design is shown in Fig. 2.

A helium stage is used to obtain the 8 K level. Three different precooling temperatures are used in its cold stage at 40 K, 25 K and 15 K to facilitate the maximum achievable performance. The 25 K temperature level is provided by a hydrogen stage. At the same time, the hydrogen stage has to establish a 15 K cooling interface solely for the purpose of the helium stage precooling. Finally, a neon-operated stage delivers the required cooling power at 40 K. Its cooling capacity is split into cooling of the METIS instrument and precooling of the helium and hydrogen stages. All three stages share the same 70 K, LN2 heat sink.

MODELING

Thermodynamic, quasi-static modeling was used to model the behavior of the sorption compressor and the cold stage. In principle the modeling of a single cooler is split into four phases and produces the coefficient of performance of the total cooler COP_{tot} (defined as the ratio between the available cooling power and the input power) as a result. This process is shown schematically in Fig. 3. First, the relevant requirements are gathered, together with material properties (1). Secondly, the thermodynamic optimization of the compressor is performed producing the coefficients of performance of a compressor as a function of the input parameters (2). Then, calculations of the performance of a cold stage are done (3). The results of the compressor and the cold-stage optimization are combined to produce the total model of a cooler. This model is used as an input to numerical optimization that seeks for operating parameters, which maximize the total coefficient of performance COP_{tot} (4). Finally, a dynamic, thermal model of a compressor cell is employed, with the parameters calculated in step 4 used as an input, to derive the size of the compressor (5).

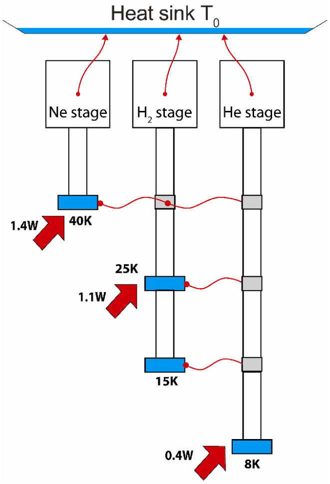

Figure 2. Schematic of the METIS sorption-cooler baseline design

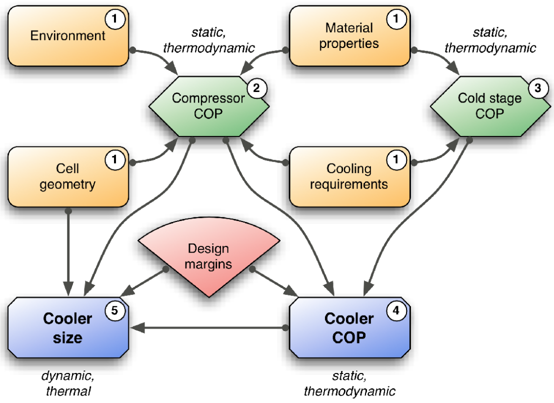

Figure 3. Sorption cooler optimization process chart

Variables that influence COP_{tot} are among others: the compressor low and high operating temperatures and pressures, the efficiencies of the cold stage heat exchangers, working gas, adsorbent material, dimensions of the compressor cells, etc. All material parameters in the model are temperature-dependent and taken from relevant material property databases[6]. The sorption isotherms were measured in an accurate setup (helium, hydrogen) or gathered from JPL (neon).

SORPTION COOLER COMPONENTS

Cold Stages

A cold stage consists of one or more counter-flow heat exchangers; pre-coolers; a Joule-Thomson restriction, which expands the high-pressure working fluid to lower pressure, reducing its temperature; and an evaporator, where liquefied gas is collected and heat from the cooled device is rejected.

In the baseline design, all heat exchangers were assumed to be 100% efficient and there is no pressure drop in the cold stage. Precooling is only applied to the high pressure lines.

A schematic of the helium and the hydrogen cold stages is shown in Fig. 4. Because the cooling temperature of the helium stage is above the critical temperature of helium (8 K vs. 5.19 K) the gas will not liquefy during the expansion. A heat exchanger is used instead of an evaporator. After the JT expansion, the helium temperature T_{exp} is lower than the cooling temperature of 8 K but higher than the critical temperature. The enthalpy difference between the 8 K level and T_{exp} is used for cooling, as shown in Fig. 5. The hydrogen stage facilitates a double JT expansion: the first to reach 25 K, and the second to produce a 15 K for helium stage precooling. After the first expansion, the working fluid is partially liquefied; therefore in the last CFHX of the hydrogen stage a two-phase flow is present. The T-s diagram of the hydrogen stage cycle is shown in Fig. 6.

Sorption Compressor and Adsorbent Material

Because of the relatively low pressure ratio, the helium and neon compressors can be built as single-stage compressors. In contrast, to provide cooling at 15 K, hydrogen has to expand to a low pressure of 0.12 bar while the optimized high pressure will be higher than 20 bar. Consequently, a two-stage compressor (see Fig. 7) is used in the hydrogen stage to achieve such high pressure ratio efficiently.

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. Therefore, as the heat sink temperature decreases, the efficiency of the sorption cooler increases, while both the size and

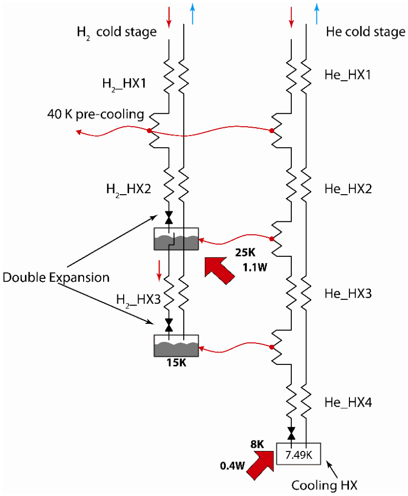

Figure 4. Schematic of the helium and the hydrogen cold stage

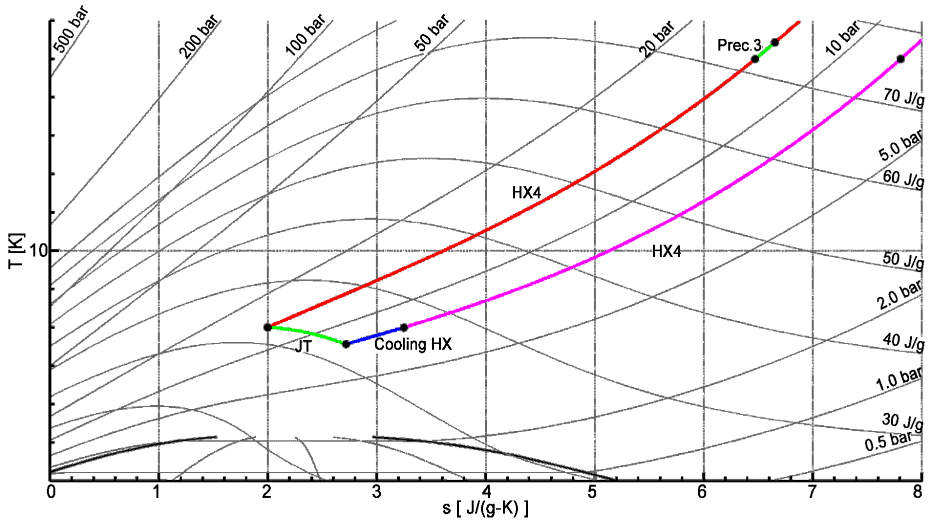

Figure 5. T-s diagram of the last part (He_HX4 and cooling HX) of the helium cold stage. The expansion takes place above the vapor dome. Therefore, a heat exchanger for vapor is needed instead of an evaporator.

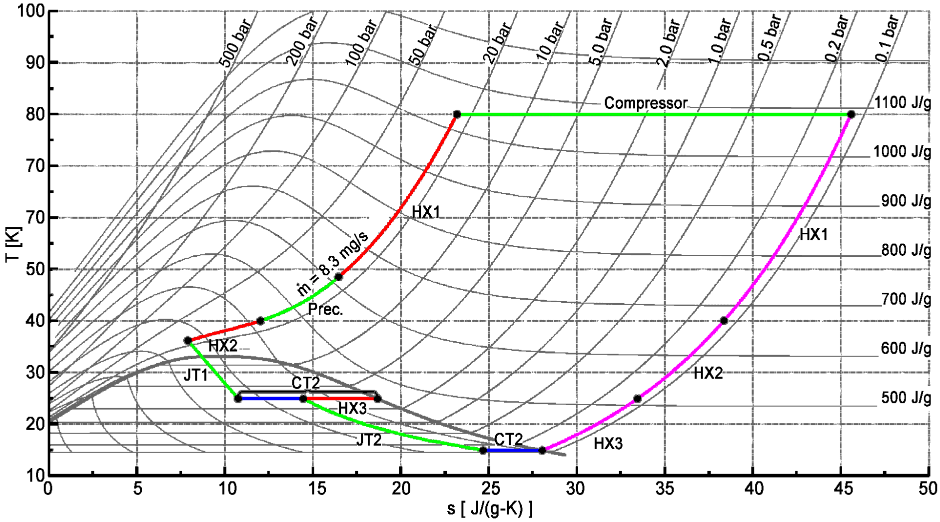

Figure 6. T-s diagram of the hydrogen cooling cycle with double expansion. Last counter flow heat exchanger, H_2_HX3, operates at two-phase region.

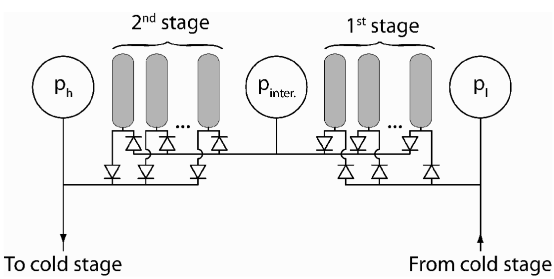

Figure 7. Schematic of two-stage compressor. Two stages are connected in serial, and buffer bottles are used at high, intermediate and low pressures. Multiple sorption cells are arranged in parallel in each stage.

the mass reduce. For the baseline design of METIS cooler system, a heat sink temperature of 70 K is considered, which can be realized by pumping a dedicated LN2 loop to reduce the pressure on the gas nitrogen exit line.

A schematic representation of a sorption compressor cell in the METIS cooler design is shown in Fig. 8. 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 the baseline design, the cells have a diameter of 2 cm and are 50 cm in length. There are multiple reasons for this choice, including the 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[7,8].

Gas-Gap Heat Switch

A gas-gap heat switch is a part of the compressor cell design. It allows for reversible switching of the thermal resistance between the sorption cell and the heat sink, as shown in Fig. 8. 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 the low value in the molecular-flow range when the cell is heated up, see Fig. 9. In this way, substantial input power and LN2 consumption are saved because the cell is thermally isolated from the heat sink and limited heat is transferred from the cell to the sink when the cell is hot. At the same time, relatively fast cool-down can be achieved, depending on the gas-gap fluid used and the width of the gap. The functioning of the gas gap greatly affects the

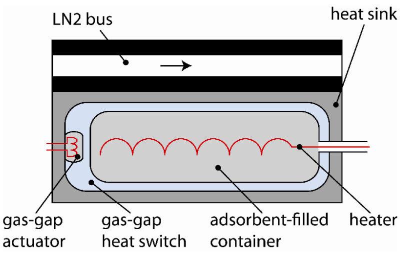

Figure 8. Schematic of a sorption compressor cell.

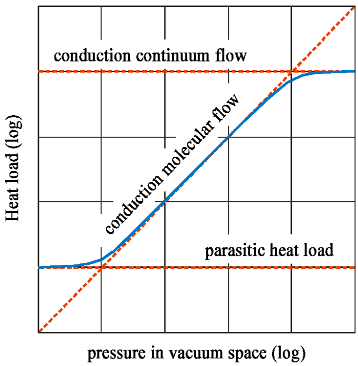

Figure 9. Schematic representation of the heat flow through a gas-gap heat switch. At very low pressures in the molecular-flow regime, the mean free path of the gas molecules is much smaller than the gap size. The smallest heat flow achievable is determined by parasitic heat load arising from radiation 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.

performance of the compressor. The parasitic conduction through the gas gap in the "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 the METIS baseline design we use a gas gap of 500 μm in width, operating with nitrogen gas.

Buffers

Buffer bottles have to be used for two reasons: to dampen the pressure variation due to the asynchronous cycling of the sorption cells and to store working gases when the system is at ambient temperature. Activated carbon can be filled in the buffer bottles to reduce their volumes.

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. There are many additional loss factors that will deteriorate the performance of the cooler. To take account of those additional losses in the design, the following margins were added to the requirements or output parameters:

- The void volume of a single, 50 cm long compressor cell was increased by 1 cm^3,
- 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 precooling 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 %.

OPTIMIZATION OF THE BASELINE DESIGN

The cooling capacities of the neon and hydrogen stages depend not just on the heat loads at the cryogenic interfaces but also on the precooling power required by the helium stage. Therefore, in the optimization process of the whole cooler chain, first the helium cooler was optimized with a cooling power of 0.5 W (0.4 W load at 8 K plus 25% margin) and as a result the input power and the required precooling powers were obtained, as well as the helium compressor mass. Since T_{exp} of the helium stage is not predetermined, the low pressure cannot be fixed either but rather it is optimized together with the other cooler parameters.

After adding the 25% design margins, the required precooling powers at 15 K and 25 K were added to the loads in the optimization of the hydrogen cooler. Because the hydrogen cooler features double expansion first to 25 K and then to 15 K, there are two possible optimization strategies. The first one is to use the fact that the pressures before and after the 2nd JT restriction are known: from this and the cooling power requirement at 15 K the mass flow can be calculated, and consequently the high pressure of the cooler, i.e. the pressure before the first JT restriction. With both the high and the low pressure set the compressor is optimized and the COP_{tot} is simply expressed as:

$$COP_{tot} = \frac{\Delta h_{cool,1} + \Delta h_{cool,2}}{\frac{\hat{q}_{IN,1}}{\Delta x_{net,1}} + \frac{\hat{q}_{IN,2}}{\Delta x_{net,2}}} \quad (1)$$

This optimization strategy neglects the fact that the compressor might operate more efficiently at a different value of the high pressure than this obtained by such analysis and in consequence the COP of the cooler might be higher. Thus here, the total cooler is optimized with only the low pressure fixed at the equilibrium-level value at 15 K. This means that, depending on the value of the high pressure there can be a mismatch between the available gross cooling powers at both cooling levels and the corresponding required values. As a result more cooling power is available than needed at one of those levels, therefore another performance measure is calculated, the effective

COP_{tot} of the cooler defined as COP_{eff}, which represents the performance of the cooler with respect to the heat rejected at the cold stage evaporators:

$$COP_{eff} = \frac{P_{cool,1} + P_{cool,2}}{\dot{m}\left(\frac{\hat{q}_{IN,1}}{\Delta x_{net,1}} + \frac{\hat{q}_{IN,2}}{\Delta x_{net,2}}\right)} \tag{2}$$

In this paper, the later optimization strategy was used.

The neon stage was calculated using the METIS 40K requirements and the precooling needs of the helium and hydrogen stages as inputs. The low pressure p_l of neon stage is fixed at the value of 13.6 bar. Very high value of p_l allows for the use of a single-stage compressor. This stage features no pre-coolers, therefore the modeling and optimization is quite straightforward. Finally, a 10% margin was added on top of the input powers, as is done for design margins

As shown in Fig. 10, a total of 0.84 kW is needed as input power that is dumped at the LN2 cryogenic bus at 70 K. In total 103 compressor cells are used of which by far most are allocated to the helium-stage cooler (87). The total amount of carbon is somewhat more than 17.8 kg of which about 15 kg is in the helium stage. Including all other materials, the total cooler mass will be around

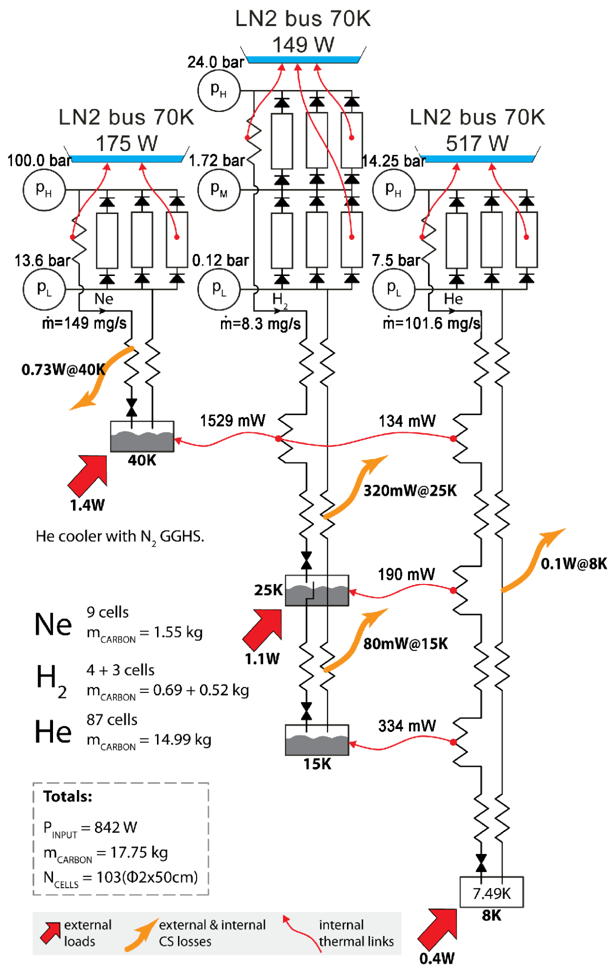

Figure 10. Schematic of the METIS sorption cooler and predicted performance

400 kg, while the exact value will strongly depend on the cooler layout and scaling with the required cooling performance.

40 K NEON-STAGE SORPTION COOLER

A detailed design has been made for a 40 K demonstrator neon cooler. With five 50 cm long cells it will be 60*40*10 cm in size and weight around 50 kg. This cooler will deliver 1 W of cooling power at 40 K, it will need around 60 W of input power corresponding to 1.25 l/h flow of liquid nitrogen at 70 K. To be realized as scaled demonstrator for METIS cooling chain, it has modular, redundant construction which allows for further, effortless scaleup to higher cooling power. An impression of the 40 K sorption cooler is given in Fig. 11.

FUTURE DEVELOPMENTS

The cooling powers that METIS requires are higher than the currently operating sorption coolers typically deliver. Thus, 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.

The adsorption capacity of helium in carbon is very limited at the current heat sink temperature (70 K). As a result, the helium stage is not efficient, and it dominates the cooler chain system in both the input power and size. There are some techniques to improve the performance and reduce the size and mass of the helium stage. Further decreasing the heat sink temperature is a straightforward method. Regenerative compressor is a solution that is widely studied and used in adsorption heat pumps at room temperature. Regeneration technique at cryogenic temperature will be studied, and demonstrated in our future demonstrator models. Furthermore, choosing another, more conducting gas instead of nitrogen in the gas-gap heat switch of the helium stage can significantly reduce the compression cycle time. Shorter cycle time results in a lower number of compressor cells that are needed to deliver the required cooling power. Consequently the size and mass of the helium stage can be reduced.

Because of the complexity of the double expansion, different cold stage arrangements for the hydrogen cooler will be studied. An optimized hydrogen cold stage design will be chosen according to the trade-off based on efficiency, complexity and manufacturability.

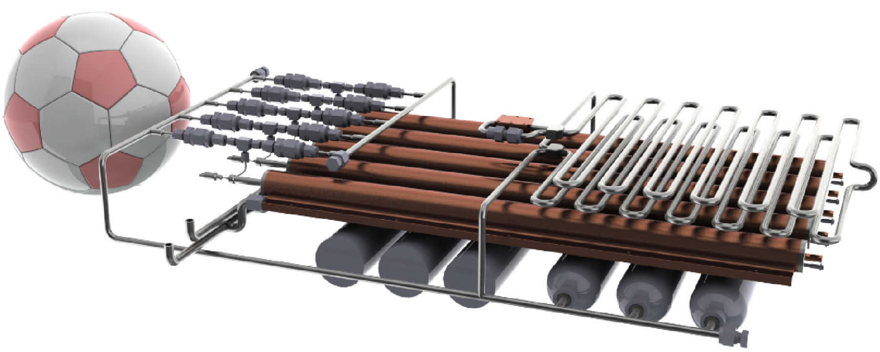

Figure 11. Impression of the neon-based sorption cooler with a cooling power of 1 W at 40 K. In the center on the top is the 40 K cold plate with close to it the Joule-Thomson restriction, and to the right the counter-flow heat exchanger. At the bottom are the buffers, and in between the buffers and the cold plate are the compressor cells. On the top left are the check valves connecting the compressor to the cold stage.

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