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) that will cover the thermal/mid-infrared wavelength range from 3 – 14 micron, and requires cryogenic cooling of detectors and optics. A vibration-free cooling technology for this instrument based on sorption coolers is 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 70 K. The latter temperature level is established by a pumped-liquid nitrogen line. The cooling powers required at the lower three levels are 0.4 W, 1.1 W, and 1.4 W, respectively. We propose a vibration-free sorption-based cooler with three cascaded Joule-Thomson (JT) coolers of which the sorption compressors are all heat sunk at the 70 K platform. A helium-operated cooler is used to obtain the 8 K level with a cooling power of 0.4 W. Here, three pre-cooling stages are used at 40 K, 25 K and 15 K. The latter two levels are provided by a hydrogen-based cooler, whereas the 40 K level is realized by a neon-based sorption cooler. In the paper, we present the preliminary design of this three-stage cooler and we discuss the developments towards a demonstrator version of this METIS cooler.

INTRODUCTION

The E-ELT, a revolutionary new ground-based telescope, will be built on a mountain top in Cerro Armazones, Chile. With its 39-metre primary mirror, E-ELT 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 [1]. E-ELT will have several science instruments and will be possible to switch from one to another within minutes. 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, 3].

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. The temperature levels of the imaging, dispersing and detecting subsystems of the instrument determine METIS’ radiometric performance. The temperatures of the optics, opto-mechanical components, and the thermal radiation shield are driven by their contribution to the overall noise budget which needs to be lower than the contributions from telescope and atmosphere. Furthermore, in configuration trade-offs, the number of different temperature levels has been reduced to four, being listed in TABLE 1.

A separate liquid nitrogen (LN2) bus system will cool the radiation shield and a backbone, respectively. All 85 K units will be thermally attached to the backbone. The three lower temperature levels, i.e. 40 K, 25 K and 8 K, will be provided by cryocooler(s). The respective heat loads at these temperature levels are also shown in TABLE 1.

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 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.

The vibration-free cooling technology based on sorption coolers is proposed for METIS instrument. Sorption coolers have been developed for over a decade at University of Twente in collaboration with Dutch Space. Apart

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TABLE 1. Required temperature levels and heat loads of METIS cryogenic 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	Heat load (W)
LM-Band Detectors	40	1.4
N-Band Imager	25	1.1
N-Band Detectors	8	0.4

from the passive valves, sorption coolers have no moving parts, which is attractive for reasons, such as long-life, vibration-free and EMI-free. It also gives flexibility in the integration with the instrument. Sponsored by ESA, a 4.5 K helium cooler [4, 5] and a 14.5 K hydrogen cooler [6] driven by sorption compressors filled with activated carbons were successfully developed and tested at the University of Twente.

CONCEPTUAL DESIGN OF METIS COOLER

Based on our experience with sorption-based cooler, we designed a sorption JT cooler chain that meets the requirements of the METIS instrument [7]. As shown in FIGURE 1, this conceptual design consists of three stages thermally linked in parallel, to obtain cooling at 40 K by a neon, 25 K by a hydrogen and 8 K by a helium-based cooler stage.

The helium stage is driven by a single-stage compressor unit and uses four counter flow heat exchangers (CFHXs), followed by a JT restriction and a cold-tip heat exchanger. In order to facilitate the maximum achievable performance, pre-cooling heat exchangers are applied at 40 K, 25 K and 15 K. Because the cooling temperature of 8 K is above the critical temperature of helium, the gas will not liquefy during expansion and a well-designed gas heat exchanger is needed to transfer the heat load to the cold helium gas at the cold tip. The 25 K temperature level is established by a hydrogen cooler. Because of the higher pressure ratio, it operates with a two-stage compressor, and the cold stage uses a double JT expansion not only to reach 25 K, required both by the METIS instrument, but also to establish the 25 K and 15 K cooling interfaces solely for the helium stage pre-cooling. Finally, a neon-operated

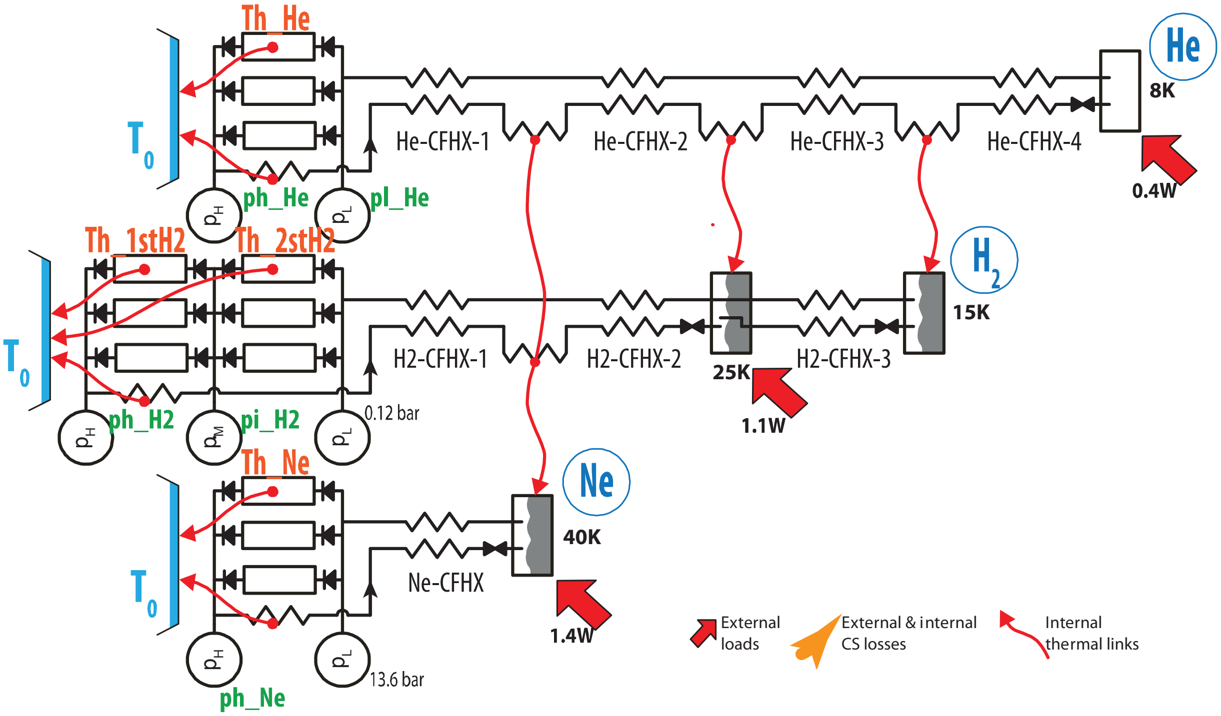

FIGURE 1. Conceptual design of METIS cooler chain.

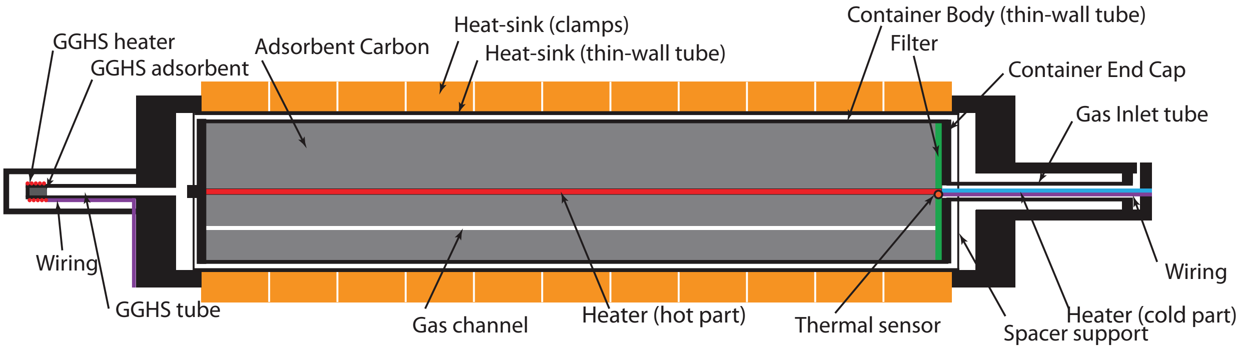

FIGURE 2. Schematic of a sorption compressor cooperating with a gas-gap heat switch (GGHS).

cooler delivers the required cooling power at 40 K. This cooler uses a single-stage compressor and its cooling capacity is split into cooling of the METIS L/M-detectors and pre-cooling of the helium and hydrogen stages.

The compressor cells are thermally attached to a cryogenic heat-sink, and gas-gap heat switches are applied in between. In all compressors saran carbon is applied. It is a type of carbon that is well studied and has been used successfully in earlier developments at the University of Twente. The amount of gas adsorbed by the carbon 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 the mass reduce. For the design of the METIS cooler chain, 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.

SYSTEM LEVEL OPTIMIZATIONS

System level modeling

A thermodynamic quasi-static model was used to optimize the operating conditions and estimate the performance of the METIS cooler chain on system level. A lumped adsorbent material filled in a cylindrical container is considered. With a specific cooling power at the cold tip, the model produces an input heating power required at the heat-sink temperature by the sorption compressor. A compressor cell of 2 cm was considered, with the length being variable. The basic cylindrical geometry was chosen based on multiple reasons, including relative ease of fabrication and the scaling of the cooler chain size as a function of the cell dimensions. At the system level, variables that influence the total input heating power, P_{tot}, are among others: the compressor low and high operating temperatures and pressures, the effectiveness of the CFHXs, working gas, adsorbent material, etc. All material parameters in the model are temperature-dependent and taken from relevant material property databases [8, 9]. The sorption isotherms were measured in special isotherm-measuring setups.

Optimization of the operating conditions: pressures and temperatures

The operating conditions include the heat-sink temperature T_0 of LN2 bus, the high temperatures T_h of compressors, and the unknown pressures, referred as p_h, p_i and pl in FIGURE 1. The input heating power was minimized to find the optimum operating condition parameters.

The cooling powers required for the neon and hydrogen stages not only depend on the heat loads from the METIS instrument but also on the pre-cooling power needed by the helium stage. Therefore, the optimization process was started with the helium stage. The input power, the required pre-cooling powers and the mass-flow rate were calculated. In the helium-stage cooler, the tip at 8 K is above the critical temperature of the working fluid. So, apart from the high pressure, the low pressure can be varied and optimized. To minimize the input power, the high temperature of the compressor and the high and low pressures of the cooler were optimized. As a result, the helium stage has to operating between 14.3 bar and 7.5 bar, and to be heated up to 109.1 K to build up the pressure. The required pre-cooling powers at 15 K and 25 K were added to the loads in the optimization of the hydrogen cooler. The hydrogen stage uses a two-stage compressor. Therefore, the intermediate pressure was also optimized. 2.0 bar and 23.8 bar were chosen as intermediate pressure and high pressure respectively in hydrogen stage. The optimum high temperatures are 135.5 K and 162.5 K for 1st stage and 2nd stage compressor respectively. The neon stage was calculated using the METIS 40 K heat load and the pre-cooling requirements of the helium and hydrogen stages as inputs. The neon stage has to thermally cycle up to 157.6 K to build an optimum high pressure of 112.0 bar. The heat-sink temperature of 70 K was selected and can be realized by a LN2 bus with pumping at the exhaust outlet.

SORPTION COMPRESSOR DESIGN

The baseline design of the sorption compressor cell is shown schematically in FIGURE 2. The cell consists of a cylindrical container that is filled with activated saran carbon. The heater is placed at the center of the carbon, and a small gas channel is drilled in the carbon to reduce the axial pressure drop. A filter is used to prevent any carbon particles from flowing into the cold stage causing clogging. A gas inlet tube connects the container to the tubing outside of the cell. Two support spacers hold the container, to maintain a gas-gap from the heat-sink. In the baseline, a small piece of ZrNi is used for actuating the gas-gap heat switch (GGHS) with hydrogen gas. It is encapsulated at the end of a thin-wall GGHS tube that connects to the gas-gap. The GGHS actuator is cycled between 60 °C and 177 °C, heated up by a manganin resistance wire wrapped around the tube, and cooled down by heat conduction through the GGHS tube.

Losses associated with a sorption compressor cell can be classified into two categories: a) internal losses, that include losses due to the parasitic thermal masses, void volume, and pressure drops. Combined with the compression process, this kind of loss is more or less proportional to the amount of carbon, and is included in the thermodynamic model presented in the previous sections. b) external losses, that include conduction, radiation, GGHS input, and heat dissipation loss of the heater. Independent from the compression process, this kind of loss is more or less proportional to the number of cells and should be evaluated separately. Following this classification, the thermal loss in the sorption compressor cell is broken-down in detail. For example, assuming perfect heat exchangers, then with a total input power of 612 W, the helium stage has 176 W loss due to the parasitic thermal masses predominantly determined by the container wall, 5 W loss associated with void volume and 21 W conduction loss. Other losses are negligibly small.

Compressor cell details were optimized to minimize the relevant losses. By taking the required number of cells, carbon amount, safety, manufacturability and ease of assembly into account, the detailed dimensions of the sorption compressor cells were determined. The inner container diameter is 17.5 mm and the length is 50 cm. Because of the different pressure ranges, the three cooler stages have different container wall thickness (Ne: 1.6 mm, H_2: 0.5 mm, He: 0.25 mm). The gas-gap width is 0.5 mm and switches between an "OFF" state of 0.5 Pa and an "ON" state of 90 Pa.

COLD STAGE DESIGN

A JT cold stage consists of one or more CFHXs, pre-coolers, JT restrictions, and evaporators. There are eight CFHXs in the METIS cooler, as labeled in FIGURE 1, operating from 70K to 40 K, 40 K to25 K, 25 K to 15 K and 15 K to 8 K. At these low temperature ranges, any tiny decrease in CFHX effectiveness will cause a considerable increase in required mass-flow rate at specific cooling power, increasing the input power and the size of the compressor [10].

An analysis of the total input power sensitivity with respect to the effectiveness of CFHXs is carried out. A minimum required effectiveness for each CFHX was given to keep the input increase less than 1.5% of the best case, while all other CFHXs were assumed to be perfect. These minima were used to define recommended values for all CFHXs, see Figure 3. With this set of recommended effectiveness values, the input and size increase is 12.7% for the neon stage, 8.7% for the hydrogen stage, 2.1% for the helium stage, and about 5.7% for the entire cooler.

TABLE 2. Required effectiveness of CFHXs.

Ref. CFHX	Min. Eff.	Recom. Eff.	Ref. CFHX	Min. Eff.	Recom. Eff.
Ne_CFHX	≥95.7%	98%	He_CFHX-1	≥98.6%	99%
H2_CFHX-1	≥91.7%	98%	He_CFHX-2	≥98.4%	99%
H2_CFHX-2	≥98.4%*	99%	He_CFHX-3	≥99.7%	≥99.7%
H2_CFHX-3	≥97.5%	98%	He_CFHX-4	≥99.8%	≥99.8%

*estimated.

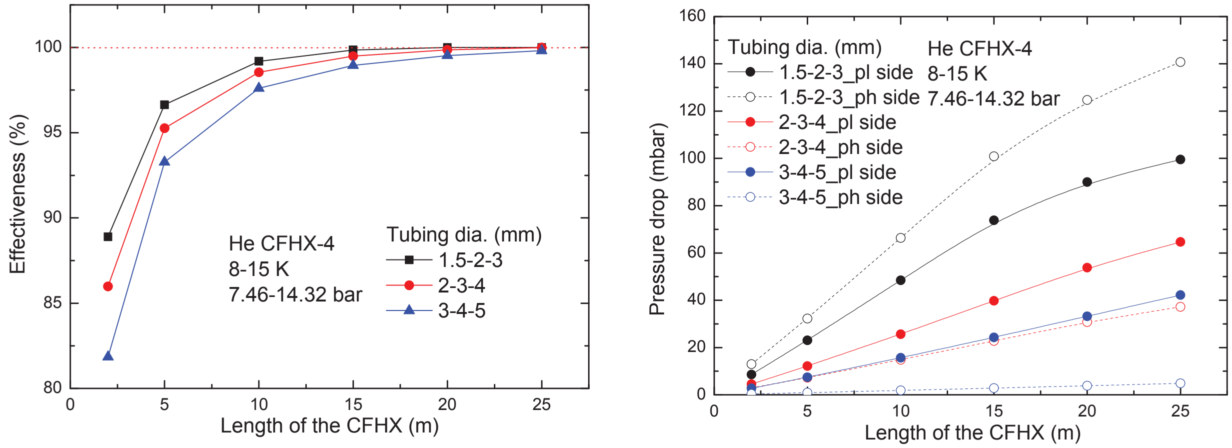

Figure 3. Static simulation of He_CFHX-4, left: effectiveness as a function of length, right: pressure drops through the tubes as a function of length. "2-3-4" in the legend indicates that the inner tube has an inner diameter of 2 mm, and an outer diameter of 3 mm, and outer tube has an inner diameter of 4 mm, and so on.

In the baseline design simple tube-in-tube CFHXs are considered. A static CFHX model is used to design the CFHXs. He_CFHX-4 is the most important heat exchanger. In order to achieve an effectiveness of 99.8%, it has to be longer than 15 m by using small tubing size, as shown in Figure 3. The pressure drop along the long tubes is less than 150 mbar, which is quite acceptable considering that the low pressure of the helium stage is higher than 7 bar. To further reduce the CFHX size, other compact types of CFHXs will be investigated in the future.

FULL COOLER PERFORMANCE

There are many additional loss factors that will deteriorate the performance of the cooler. To account for these additional losses, 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,

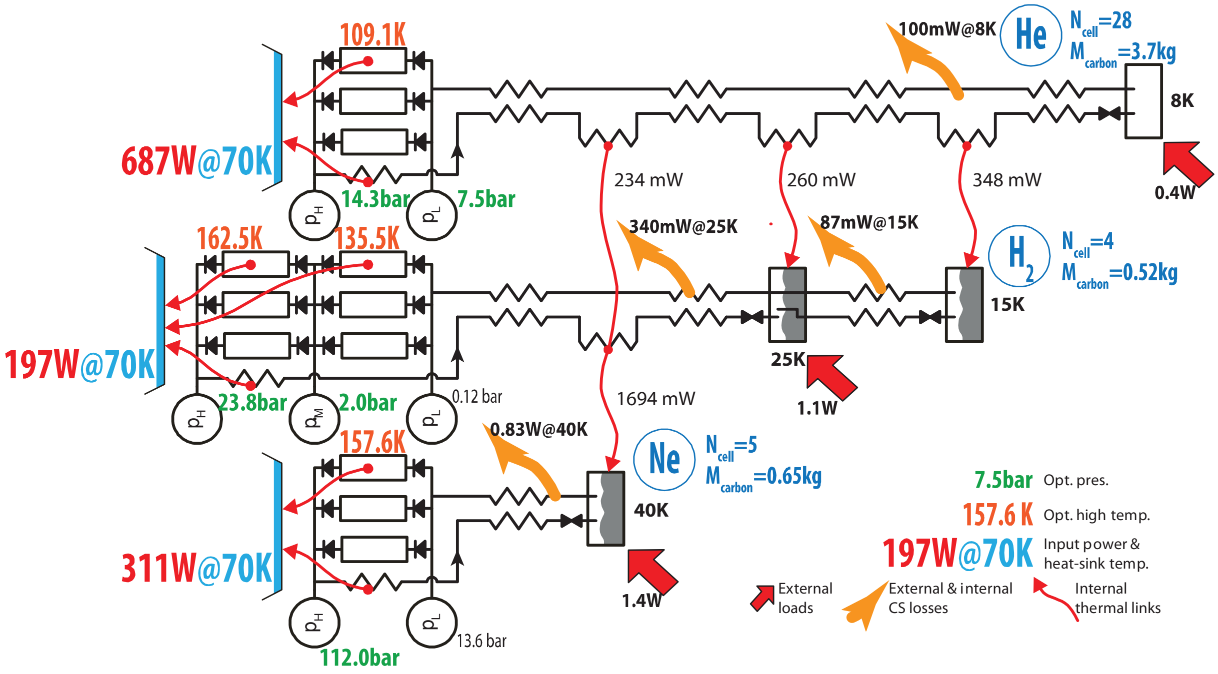

FIGURE 4. Basic performance of the METIS cooler, based on loss budget and margins, with recommended CFHX effectiveness listed in TABLE 2.

- 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 10 %.

On the basis of the above loss budget and margins, the total input power required by the METIS sorption cooler is evaluated incorporating all losses associated with the compressor cells and the ineffectiveness of CFHXs in the cold stages. The basic performance of the METIS cooler is calculated and presented in FIGURE 4.

DEMOSTRATOR MODELS FOR METIS COOLER

Currently the development and test of three major demonstrator models are under development.

- Neon 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.
- Scaled helium sorption compressor: A scaled-down version of the METIS helium compressor stage will be developed and tested which 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 about 10% of the METIS helium compressor stage. The aim is to validate the performance of a scaled-down METIS helium compressor, in particular regarding cell sizes and adsorption temperature.
- Helium cold stage: A cold stage for the helium-based sorption cooler will be developed and tested in parallel to the helium compressor development. 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.

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