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Development of a sorption-based Joule-Thomson cooler for the METIS instrument on E-ELT

Y Wu[1], C H Vermeer[1], H J Holland[1], B Benthem[2], and H J M ter Brake[1]

[1] University of Twente, P.O. Box 217, 7500AE, Enschede, Netherlands

[2] Airbus Defence and Space Netherlands B.V., P.O. Box 32070, 2303DB, Leiden, Netherlands

E-mail: y.wu@utwente.nl

Abstract. METIS, the Mid-infrared E-ELT Imager and Spectrograph, is one of the proposed instruments for the European Extremely Large Telescope (E-ELT) that will cover the thermal/mid-infrared wavelength range from 3-14 m. Its detectors and optics require cryogenic cooling at four temperature levels, 8 K for the N-band detectors, 25 K for the N-band imager, 40 K for the L/M-band detectors and 70 K for the optics. To provide cooling below 70 K, a vibration-free cooling technology based on sorption coolers is developed at the University of Twente in collaboration with Airbus Defence and Space Netherlands B.V. (former Dutch Space B.V.). We propose a 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. To validate the designs, three demonstrators were built and tested: 1. Full-scale 8 K helium JT cold stage; 2. Scaled helium sorption compressor; 3. Scaled 40 K neon sorption JT cooler. In this paper, we present the design of these demos. We discuss the experiment results obtained so far, the lessons that were learned from these demos and the future development towards a real METIS cooler.

1. Introduction

The European Extremely Large Telescope (E-ELT) is European Southern Observatorys revolutionary new concept of a ground-based telescope for optical/near-infrared range. With its 39-metre primary mirror on the sky, E-ELT will gather 15 times more light than the largest optical telescopes operating at the time of its development and vastly advance astrophysical knowledge. It will 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 scientific instruments, and it will be possible to switch from one instrument to another within minutes. Eight different instrument concepts and two post-focal adaptive modules are currently being studied. METIS, the Mid-infrared E-ELT Imager and Spectrograph, is one of those proposed instruments, and will offer imaging and spectroscopy over the wavelength range of 3-14 microns, covering the L, M and N bands [2, 3].

METIS consists of a warm part including instrumentation, structural supports and a vacuum vessel in ambient, and of a cold part inside the vacuum vessel that includs the cold optics and detectors. The operating temperature levels of the imaging, dispersing and detecting subsystems

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

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

of the instrument are determined by METIS radiometric performance. The detectors require approximately 40 K and 8 K for the L/M and N band, respectively [3]. The temperatures of the optics, opto-mechanical components, and the thermal radiation shields are driven by their contributions to the overall noise budget that needs to be lower than the contributions from telescope and atmosphere. Performance analysis yields maximum allowable temperatures of 85 K for all cold modules, except for the N-band imager, which has to be cooled to below 30 K [3]. Furthermore, in configuration trade-offs, the number of different temperature levels has been reduced to four, being listed 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. Therefore, a vibration-free cooling technology based on sorption JT coolers is proposed for the METIS instrument. As schematically shown in Figure 1, a sorption JT cooler uses a sorption compressor that contains adsorption material, such as activated carbon. By heating and cooling in a cyclic manner, the adsorbent material adsorbs and desorbs the working fluid. It thus can produce a steady DC flow for the JT cold stage with passive valves regulating the flow direction. Apart from a few passive check valves, sorption JT coolers have no moving parts, which is attractive for a number of reasons: they are vibration-free, EMI-free and have the potential of a long lifetime. It also gives flexibility in the integration of the cooler

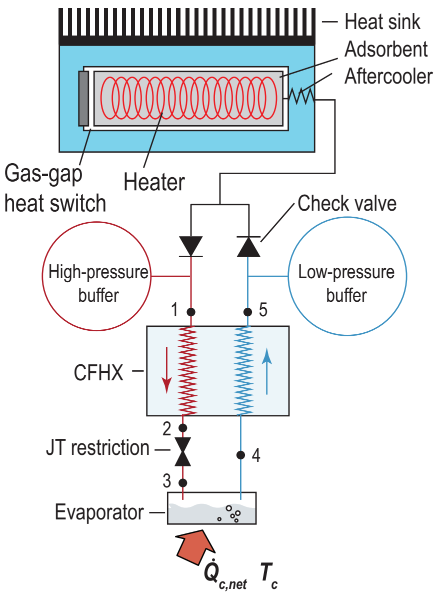

Figure 1. Schematic of a sorption JT cooler.

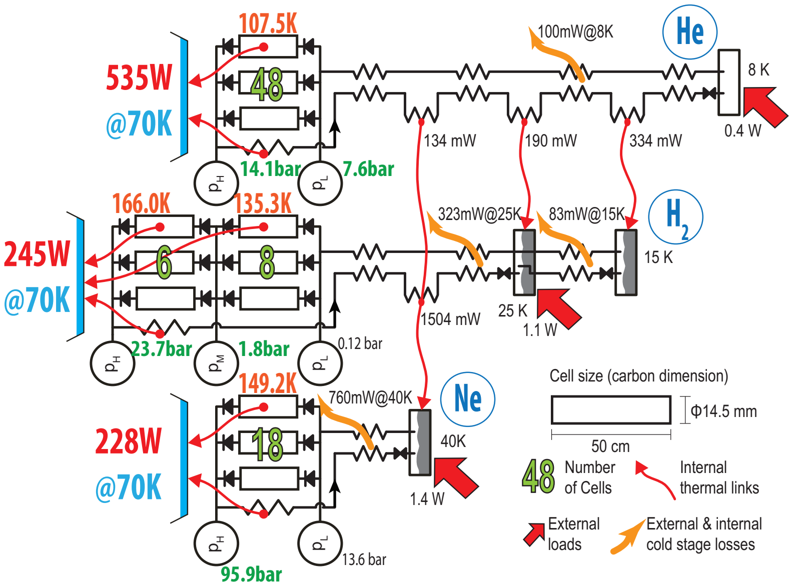

Figure 2. Schematic of the design of the METIS cooler chain. Optimized operating parameters, cell size and number of cells, as well as estimated performance are presented [4].

with the instrument.

Based on our experience with sorption-based coolers, we designed a sorption Joule-Thomson (JT) cooler chain that meets the requirements of the METIS instrument [5]. As shown in Figure 2, this conceptual design consists of three stages thermally linked in parallel, to obtain cooling at 40 K, 25 K and 8 K individually. The compressor cells of all stages are heat sunk at a 70 K pumped liquid-nitrogen bath. Neon, hydrogen and helium are selected as working fluids for the three stages, respectively [6]. In the preliminary design, the basic operating parameters, such as the high and low pressures and the high operating temperatures of the sorption compressors were optimized, aiming at a minimum input power [4]. Based on this preliminary design, a detailed design of the components in the cooler chain was carried out. The performance and the size (the dimension and the number of the sorption compressor cells) were evaluated and updated. These are included in Figure 2.

To demonstrate the validation of the sorption JT technology for such large ground application and to validate the design, three demonstration setups were planned based on the baseline design of the METIS cooler chain:

(i) Full-scale 8 K helium JT cold stage. This demo is representative of the helium stage in the METIS cooler chain in terms of cooling power, cooling temperature and mass flow, but it is driven by a mechanical compressor. Precooling (70 K and 15 K) is supplied by a conventional mechanical refrigerator. The aim is to validate the cold stage performance, in particular regarding the 15-8 K counter flow heat exchanger (CFHX), the 8 K cold heat exchanger (CHX) and the JT restriction.

(ii) Scaled helium sorption compressor. The second demo is a scaled version of the helium compressor in the METIS cooler chain, which contains sorption compressor cells of sizes representative for METIS and operates with the same heat-sink temperature as the METIS cooler. However, the number of the cells is limited to about one tenth of the METIS helium compressor (which requires 48 cells). The aim is to validate the performance of the helium sorption compressor, in particular regarding coefficient of performance, cell size and the dynamic behavior of the sorption compressor.

(iii) Scaled 40 K neon sorption cooler. This is a complete neon-stage demo-cooler establishing about one fourth of the required cooling power of the neon stage cooler for METIS. The purpose is to demonstrate a full-functional sorption cooler and validate the design of the critical components.

2. Full-scale 8 K helium JT cold stage

This demonstration setup focuses on the 15-8 K part of the helium stage in the METIS cooler chain, including the 15-8 K CFHX, the 8 K CHX and the JT restriction. Figure 3 presents a schematic overview of this setup. A powerful two-stage GM cooler, Sumitomo RDK-408D2, simulates the neon and hydrogen stages in the METIS cooler chain to supply precooling at intermedium temperatures (70 K and 15 K in this setup). CFHX-1 and CFHX-2 were configured as tube-in-tube heat exchangers wound into helical coils that surround the GM cooler providing precooling from 300 K to 15 K with two precooling heat exchangers (preHXs) that were thermally attached to the GM cold head. Two radiation shields were built and thermally linked to these cold head as well. The flow of the JT cold stage was driven by a mechanical compressor, Leybold RW-2. Furthermore, for speeding up the initial cool down of the 15-8 K part, a bypass line (BL2) was connected the cold end of the high-pressure line and the warm end of the low-pressure line. Valve BV2 was used for regulating the bypass flow rate.

All CFHXs were configured as tube-in-tube. PreHXs were made of stainless steel tubing wound on the cold head of the GM cooler with soldering contact. The 8 K CHX was made of stainless steel tubing wound on a copper cylinder with soldering contact. The dimensions

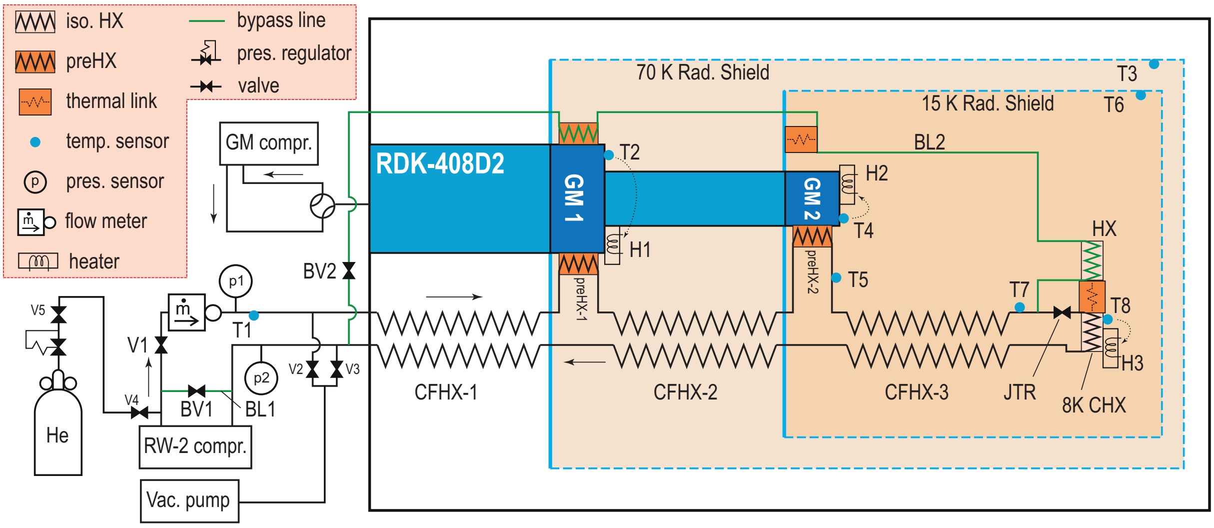

Figure 3. Schematic of the 8 K helium JT cold stage setup.

Table 2. Dimensions and estimated performance of the heat exchangers in the helium JT cold stage setup.

HX	D (outer/inner, mm)	L (m)	ϵ	Δp (high/low, mbar)	T_{out} (high/low, K)	$\dot{Q}_{preC}$ (W)
CFHX-1	8*1 / 5*1	1.5	90.17%	7.96 / 76.92	91.92 / 272.89	-
PreHX-1	5*1	0.8	99.86%	1.27	70.03	12.11
CFHX-2	8*1 / 5*1	2.4	89.34%	2.83 / 15.25	21.15 / 64.03	-
PreHX-2	2.5*0.4	2.0	99.98%	14.21	15.00	3.97
CFHX-3	6.35*1.24 / 3.25*0.71	11.5	99.97%[a]	45.36 / 137.65	8.00 / 14.98	-
8 K CHX	3.25*0.71	0.8	99.96%	2.69	8.00	0.50

[a]99.8% is required.

and simulated performance of the heat exchangers in the setup are listed in Table 2. The JT restriction in this setup was made of a capillary tube with an inner diameter of 203 m and a length of 14.8 cm.

With an average measured mass flow rate of 99.95 (100.0±0.7) mg/s, an average cooling power of 0.422 (0.422±0.002) W was measured at 7.98 (7.98±0.3) K. The high and low pressures measured at room temperature were 14.96 (14.96±0.05) bar and 7.31 (7.31±0.05) bar, respectively. Based on the measured mass-flow rate, the pressure drop in the high-pressure line is 67.73 mbar and in the low-pressure line 219.61 mbar. Then, the estimated pressures before and after the JT expansion were 14.89 bar and 7.53 bar. The cooling temperature was stabilized in a range of 0.07 K and the cooling power was maintained in a range of 0.07 W. By assuming the CFHX-3 to be ideal, the calculated gross cooling power at the 8 K cold tip is 0.482 (0.48±0.09) W according to the measured mass flow rate and the evaluated pressures.

Table 3 summarizes the operating pressures and performance including cooling temperature, power and mass flow rate comparison between calculated and experimental data. Compared to the design, the measurement shows 3.60% less flow rate but 11.84% more pressure difference. The flow impedance of the entire JT cooler is roughly 23% higher than calculated. This is mostly caused by the capillary JT restriction. In choosing the length, we neglected the entrance effect. The entrance length can be 150 times of the hydraulic diameter considering the Reynolds number is about 17000 at the inlet of the JT restriction. The friction factor at the entrance region should be increased by a minimum of 10% according to Ref. [7]. In addition, we expect some oil of the RW-2 compressor has entered the system and caused some fouling of the heat

Table 3. Operating pressures and performance comparison between the calculation and the measurement of the 8 K helium JT cold stage.

	Ideal optimized value	Measured values	
High pressure, bar	14.08	14.96(14.89[a])	+6.25%(+5.75%[a])
Low pressure, bar	7.62	7.31(7.53[a])	−4.07%(−1.18%[a])
Pressure difference, bar	6.46	7.65(7.36[a])	+11.84%(+11.39%[a])
Cooling temperature, K	8.00	7.98	−0.25%
Cooling power, W	0.5[b]	0.422(0.482[c])	−15.60%(−3.60%[c])
Mass flow rate, mg/s	105.83	99.95	−5.56%

[a] Estimated pressures before and after the JT expansion according to the calculated pressure drops and measured pressures.
[b] 0.4 W specification + 25% desgin margins
[c] Evaluated gross cooling power according to the estimated pressures before and after the expansion.

exchangers.

3. Scaled helium sorption compressor

The purpose of this demonstration setup is to verify the design and performance of the most critical sorption compressor in the METIS cooler chain, the helium sorption compressor. The parallel operation of the sorption compressor cells allows us to work with a down-scaled version using only a limited number of cells. The setup was designed for four full size (Ø14.5*500 mm) helium compressor cells, as an assembly expected to deliver a flow rate of 8.90 mg/s between 7.62 bar and 14.08 bar operating at a heat-sink temperature of 70 K.

Figure 4 is the schematic layout of the scaled helium sorption compressor setup. Four cells surround the cold head of a GM cooler that provides the 70 K heat sinking. Cells are

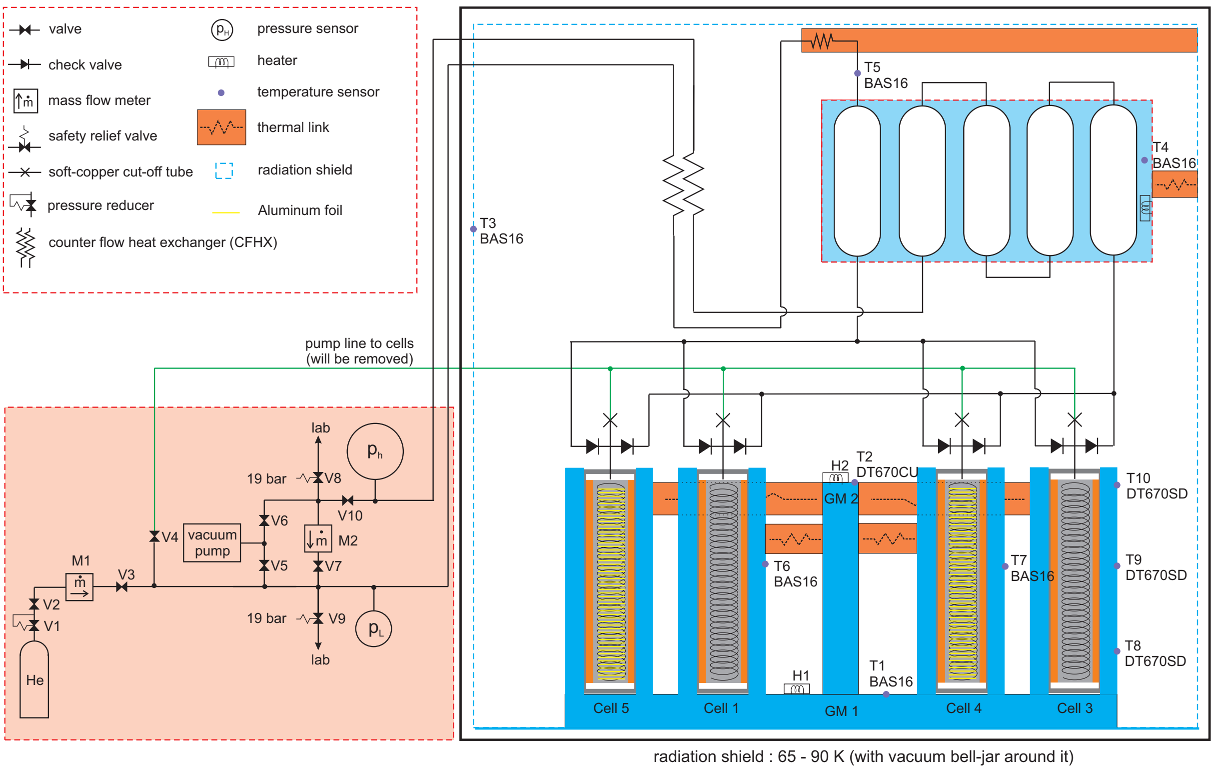

Figure 4. Schematic of the scaled helium sorption compressor setup.

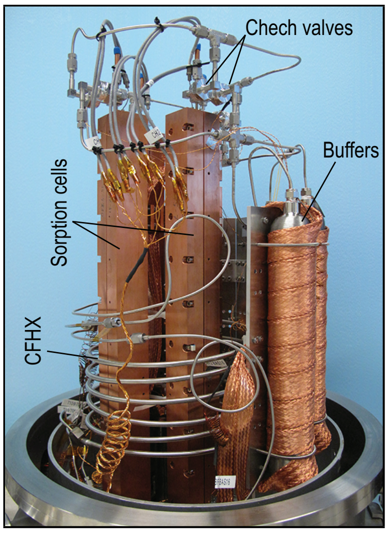

Figure 5. Photo of the scaled sorption compressor setup.

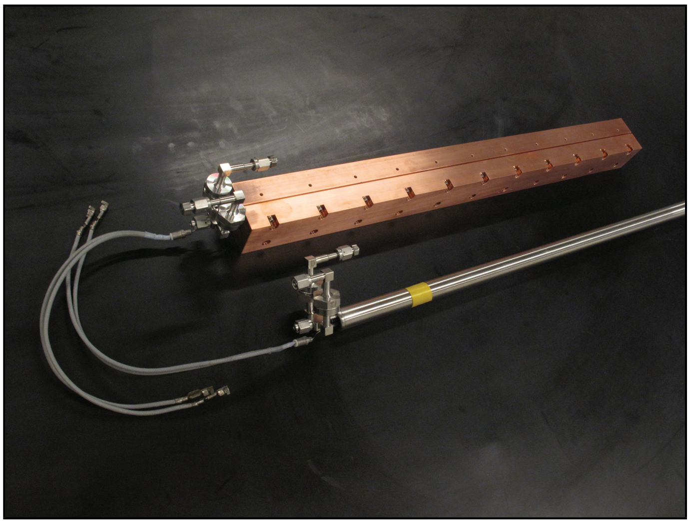

Figure 6. Photo of Sorption compressor cell assembly.

directly mounted onto the 1st stage cold plate of the GM cooler. To create a uniform heat-sink temperature along the half meter long cells, extra thermal links were installed between the 2nd stage of the GM cooler and the top of the cells. Several buffers are connected in series to smoothen the pulsed out-flow from the cells and to reduce the storage pressure of the system at room temperature. The buffers, as well as the radiation shield, are thermally attached to the 1st stage cold plate of the GM cooler. The cold pressurized flow generated by the compressor is warmed up to room temperature through a CFHX by the returning flow and then measured by the mass-flow controller M2. The high-pressure flow is restricted via M2 and valve V7 to the low pressure. Figure 5 shows the scaled helium sorption compressor-cell setup assembly.

The sorption compressor cells in this setup are filled with saran carbon pills of 14.5 mm diameter. They are operated with a weak thermal contact to the heat sink that, in this setup, is realized by thick copper blocks as shown in Figure 6. Six cells (numbered 1 to 6) were manufactured and assembled. Four cells (Cell 1, 3, 4 and 5) were selected and installed in the setup. Cells 4 and 5 are equipped with 40 μm thick aluminum foil placed in between the carbon pills, so as to enhance the radial conductance. Cells 1 and 3 are baseline cells without aluminum foils between the carbon pills. A default setting was chosen according to the simulation results of our sorption compressor model: pulsed heating power for each cell 150 W, heating time 8.73 s, cycle time 103.6 s, heat-sink temperature 70 K and high pressure 14.08 bar. The setup was first tested with single-cell operation. The performance of the individual cells operating at nominal

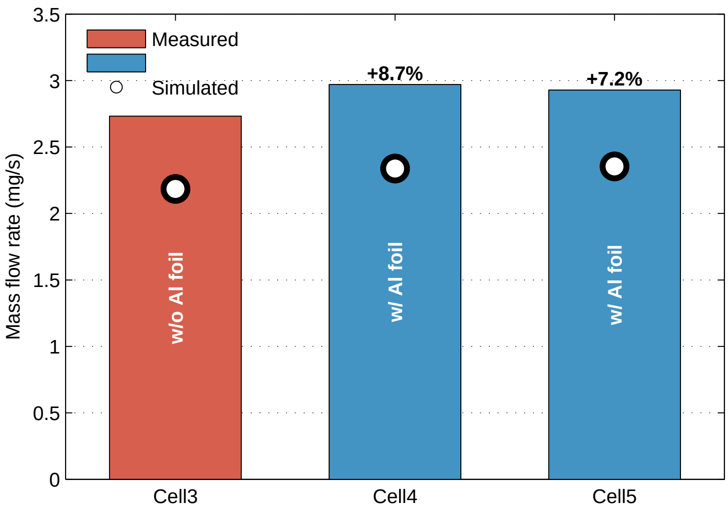

Figure 7. Measured average mass flow rate comparison between Cell 3, 4 and 5.

conditions was tested. The heater of Cell 1 appeared to have a cryogenic defect probably caused by some internal shrinkage effect in the heater. The other cells could be operated successfully. An average flow rate of 2.73 (2.73±0.05) mg/s was measured for Cell 3 operating from an average low pressure of 7.48 (7.48±0.05) bar to the set high pressure of 14.08 bar. In the single-cell operation mode, the pressure oscillations at the high- and low-pressure sides are both about 0.4 bar. These pressure swings influence the performance of the sorption compressor since they allow the cell to produce an out-flow at relatively higher pressure and to adsorb an in-flow at relatively lower pressure. According to T8, T9 and T10 (see Figure 4), the average heat-sink temperature of the half-meter long copper heat sink is evaluated, and it is 70.6 (70.6±0.5) K. Cell 4 and Cell 5 were tested at the same conditions. Figure 7 shows the measured performance of the three cells. The radial conductance enhanced cells (Cells 4 and 5) generated higher flow rates than the baseline cell (Cell 3) by 8.7% and 7.2%, respectively. The simulated performance based on a 1D sorption compressor model was also presented in Figure 7. The measured performance deviates from the simulated performance by about 25%. Furthermore, multi-cell operation was performed by cycling Cells 3, 4 and 5 with 120° phase difference. With an average heat-sink temperature of 70.4 K, a total average flow rate of 9.19 (9.19±0.08) mg/s was achieved. In the multi-cell operation, the oscillation at the low-pressure side was reduced compared to the single-cell operation. Therefore, the total flow rate is higher than the sum of the flow rates that were measured in the single-cell operation. According to the flow rate we measured, the helium stage of the METIS cooler chain would require only 35 cells instead of 48 in the design.

4. Scaled 40 K neon sorption cooler

The scaled 40 K neon sorption cooler was designed to demonstrate the feasibility of the sorption cooler technology for the METIS instrument. It is designed to produce 1.0 W cooling power at 40 K with a flow rate of 35.6 mg/s and a heat-sink temperature of 70 K. The design of this demonstrator was based on the preliminary system design. Here, the high pressure of the neon stage was 112 bar, whereas it was adapted to 95.9 bar in the later detailed design (see Figure 2). A CAD overview of the cooler is presented in Figure 8.

Taking a 25% design margin in the cooling power, five sorption compressor cells are needed for providing the required flow rate. The sorption compressor cells are mounted on an isothermal

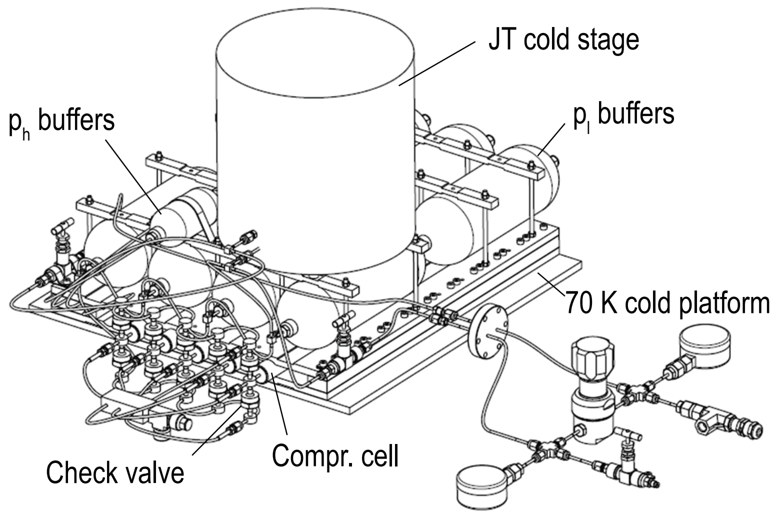

Figure 8. CAD overview of the 40 K neon sorption cooler.

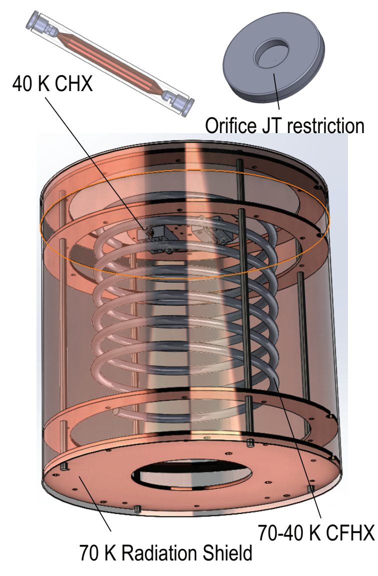

Figure 9. The neon sorption compressor assembly.

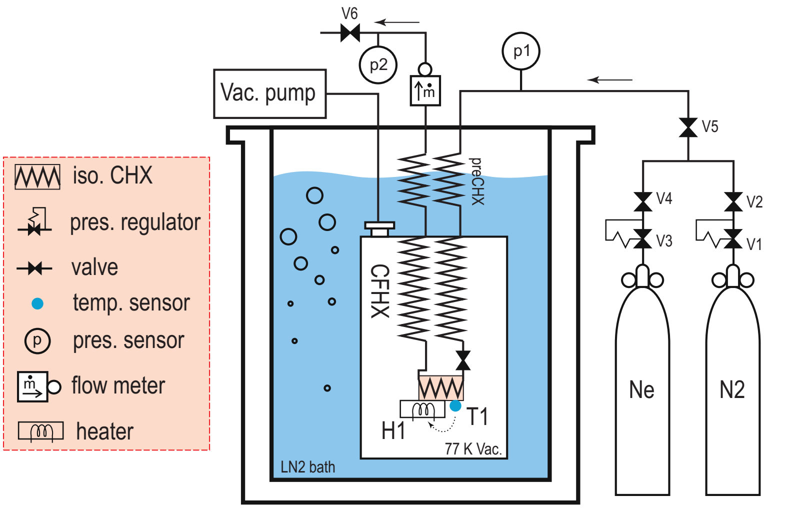

Figure 10. Schematic of the neon JT cold stage testing setup.

cold platform that will be cooled down to 70 K by liquid nitrogen bath. Buffers and check valves are arranged in the same way as in the scaled helium sorption compressor. The cells in this setup are also similar to those in the helium sorption compressor but with thicker insulation layers and container. The compressor module was designed by University of Twente, and fabricated by Airbus Defence & Space Netherland.

As shown in Figure 9, the JT cold stage of the scaled neon sorption cooler consists of a CFHX operating from 70 K to 40 K, a JT restriction through which the high-pressure flow of 112 bar expands isenthalpicly to 13.6 bar, and 40 K CHX that is able to extract 1.0 W cooling power from the two phase neon fluid with minimum temperature difference. The CFHX is made of two 3 meter long stainless steel tubes that are brazed side by side. It is designed to have an effectiveness of 98.7% with a maximum pressure drop less than 1 mbar. The JT restriction is a laser-machined micro orifice with a diameter of 25 μm in a stainless steel disk. The disk is clamped in a Swagelok VCR connector. The 40 K CHX module is made of stainless steel tubing with a copper insert. The copper insert is a cylinder with micro grooves machined by EDM. These grooves are 400 m wide and create micro flow channels with a hydraulic diameter of 800 m. Within a length of 30 mm, the CHX module has a heat transfer area of about 11 cm2. The temperature difference for heat transfer in the CHX was assumed to be 0.5 K. A moderate heat transfer coefficient of 0.1 W/(cm^2-K) was chosen based on free convection in the boiling neon [8]. Therefore the CHX requires 20 cm2 heat transfer area for 1.0 W. Two such modules were clamped in aluminum bases that were mounted on the 40 K cold plate.

The neon JT cold stage was first tested in an open loop system. Figure 10 is a schematic of the test setup. The cold-stage assembly shown in Figure 9 was placed in a vacuum chamber that was submerged in a liquid-nitrogen bath. The high-pressure neon flow was provided by a neon gas bottle with pressure regulator (V3) and then precooled by the liquid nitrogen before entering the JT cold stage. The low-pressure flow was regulated by a valve (V6) before being exhausted into the atmosphere. In order to save neon gas, the cold stage was first precooled to 77 K using nitrogen as the working fluid. It took about 5 hours to cool the cold stage from room temperature to 83 K (T1). Then the working fluid was switched to neon to further cool down. A cooling power of 1.00 W at 40 K was measured with a mass flow rate of 44.0 mg/s (Note that the flow rate is higher since the warm-end temperature of the cold stage in this test is 77 K instead of 70 K) and a high pressure of 112 bar. The ideal gross cooling power was calculated to be 1.025 W, the corresponding net cooling power was 0.985 W taking into account the CFHX inefficiency and other parasitic losses. The calculated mass flow through the JT restriction is 47.8 mg/s. The measured flow rate is in the range of 8% of the calculated value indicating that the design of the orifice restriction is quite successful. With the measured flow rate, the cold stage will produce 1.24 W gross cooling power when it operates from 70 K. However, to achieve

40 K, the low pressure had to be reduced to 10 bar corresponding to a boiling temperature of 37.54 K, instead of the design value of 13.57 bar (T_{vap} = 39.5 K). This indicates that the temperature difference that is required for the 1 W heat transfer in the 40 K CHX is about 2.5 K which is much higher than the design assumption of 0.5 K. We expect this to be caused by a bad thermal contact between the copper insert and the stainless steel tube in the CHX. The copper insert is suspended in the stainless steel tube leaving a small gap in between. This gap will be a major thermal resistance in the thermal path from the two phase neon flow to the 40 K cold plate. In the future, this 40 K CHX will be redesigned.

The neon sorption compressor is similar to the helium compressor of the second demonstrator. The carbon pills are 14.29 mm in diameter and the insulation layer is 2.82 mm thick and made of Telfon. The length of the cell is 0.5 m. Currently the neon compressor is under construction at Airbus Defence and Space Netherlands. Once it is completed, the neon cold stage will be coupled to the compressor. Full-system test experiments for the entire cooler will be carried out.

5. Summary

Three demonstrators were built and tested to validate the theoretical design of the METIS sorption cooler. The full-scale 8 K helium JT cold stage is able to deliver 0.422 W cooling power at 8 K which is above the requirement (0.4 W) and within the design margin. The scaled helium sorption compressor setup successfully validates the switchless configuration for the sorption compressor cell, and its performance validates the theoretical model used for design. Three cells could establish a flow of 9.19 mg/s. Thus, the required flow rate of 105.8 mg/s in the METIS cooler would require 35 cells instead of the 48 cells in the design. Furthermore, a 40 K neon sorption JT cooler setup is designed and fabricated. The cold stage of this cooler was tested in open loop, and 1.00 W at 40 K was achieved as expected. The compressor cells for this neon cooler demo are under construction at Airbus Defence and Space Netherlands and, after completion, these will be combined with the cold stage for full-system test experiments.

Acknowledgments

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