Development of a 2K Joule-Thomson Closed-Cycle Cryocooler

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ABSTRACT

The Rutherford Appleton Laboratory (RAL) is currently developing a *2K Joule-Thomson cooler* targeted at future space science missions requiring low temperatures, for example as part of the cryogenic chain for the ESA Athena X-ray telescope. The cooler builds on previous closed cycle cooler developments at RAL, in particular the very successful 4K-JT cooler that was flown on the ESA Planck mission. However the working fluid for the 2K-JT cooler will be ^3He, and two extra stages of compression have been added to provide a much lower effluent pressure and a greater overall compression ratio. The design of the 2K-JT cooler is described, with reference to lessons learnt from Planck in-orbit data, and results of the test program to date are presented.

INTRODUCTION

Cryocooler development for space applications has been ongoing for over 30 years at RAL[1], and has resulted in a range of closed cycle mechanical cryocoolers covering temperatures from 2 K to 80 K and above. These coolers have been licensed to both UK and US industry and have subsequently underpinned a large variety of high profile scientific and operational missions; ranging from space exploration and the origins of the universe, to earth observation, climate change, and weather forecasting.

One of those developments was a 4K Joule-Thomson (4K-JT) cooler[2] which was flown on the ESA Planck mission[3] to observe the fluctuations of the Cosmic Microwave Background. As part of the cryogenic chain[4] for the High Frequency Instrument (HFI), the 4K-JT cooler was precooled passively at 54 K by the spacecraft radiators and actively at 18 K by a hydrogen JT cooler supplied by JPL. The cooler was able to produce 20 mW of cooling at 4.5 K with a pre-cooler temperature of 17 K. Some in-orbit results are presented below and discussed within the context of the current RAL JT cooler developments.

Following on from the Planck 4K-JT cooler, RAL are currently developing a 2K-JT cooler targeted toward the Athena X-ray telescope[5], which has been selected as the second L-class mission in ESA's Cosmic Vision plan, with launch foreseen in 2028. As part of the cryogenic chain[6] for the X-ray Integral Field Unit instrument (X-IFU)[7] the present baseline is that the 2KJT cooler will be pre-cooled passively at 120 K-150 K by the spacecraft radiators and actively at 15 K by a pulse tube cooler. The cooler is required to provide 20 mW of pre-cooling at 2 K to service a hybrid ^3He sorption-ADR cooler operating at 50 mK. The 2K-JT cooler will retain much of the Planck 4K-JT cooler heritage, in particular the heat exchanger and thermal interface architecture. However, the requirement of a 2 K interface drives the use of ^3He as the working fluid, operating at a vapour pressure of $\leq$200 mbar in the effluent line.

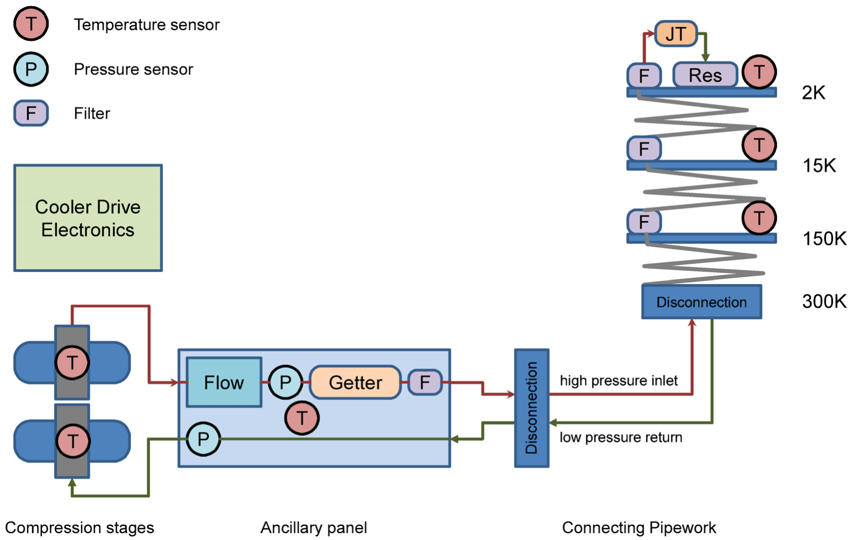

Figure 1. Schematic of the 2K-JT cooler system.

COOLER ARCHITECTURE AND INTEGRATION WITH SPACECRAFT

The 2K-JT cooler schematic is shown in Figure 1. The cooler comprises four reciprocating linear motor compression stages to perform an expansion of the gas across a JT restriction. The compressors are equipped with an arrangement of reed valves and buffer volumes in order to produce a steady flow of gas. The gas must be pre-cooled prior to the expansion taking place, and, to reduce the heat rejected at the pre-cooling interfaces, counter-flow heat exchangers are used between the stages. An ancillary panel carries gas handling and measuring equipment, as well as filters and a reactive getter to ensure gas cleanliness, which is critical to the long term operation of the cooler. The cooler is controlled by a set of drive electronics which perform all commanding and controlling functions as well as providing the electrical input power for the compressors and returning the cooler housekeeping data.

Also shown is a set of disconnection plates and connecting pipework that allow the system to be broken into several pieces to aid integration. An advantage of the JT cooler architecture is that the cooling is delivered remote from the compressor mechanisms which means that most of the cooler parts, i.e. almost all the mass and all those requiring significant electrical power, may reside in the Service Module part of the spacecraft at ambient temperatures. This greatly reduces the possibility of unwanted mechanical and electrical perturbations from those items being manifest at the detectors. In addition the heat exchanger pipework lends itself to easy manipulation which gives great flexibility when selecting a route through the Payload Module to deliver cooling remotely. A disadvantage of the distributed nature is that it is undesirable to integrate as a complete unit. The connecting pipework, which can be designed to suit the specific spacecraft architecture, allows these two parts to be delivered and integrated to the spacecraft separately, with a final purge and fill procedure being carried out afterwards.

HEAT EXCHANGER ASSEMBLY

The heat exchangers are a tube-in-tube counter-flow design that makes use of the effluent gas to remove enthalpy from the high pressure inlet gas in order to reduce the heat rejected to each of the pre-cooling stages. At the interfaces to each of these stages there are filters to ensure good thermal contact to the stage and also to trap any impurities in the gas. On the 2K-JT thermal interface there is a filter prior to the JT orifice and a sintered reservoir afterwards. The reservoir retains any liquid produced during the expansion and prevents sloshing and flash evaporation affecting the temperature stability. Figure 2 shows the masses and size envelopes of the pre-cooling and 2K-JT interfaces, and shows an annotated photograph of the 150 K interface under test configuration.

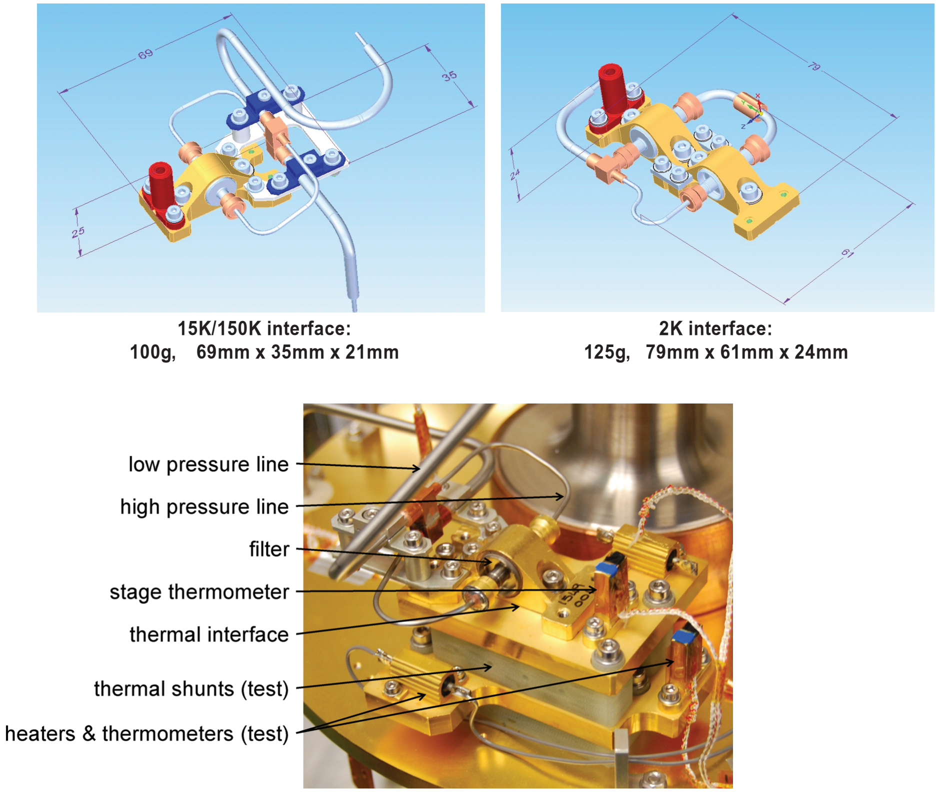

Figure 2. 2K cooler heat exchanger interfaces (top) and the 150K interface under test (bottom).

Heat Exchanger Modelling

The design of the heat exchangers dictates the heat load on the pre-cooling stages to a great extent. A model of the heat exchanger system originally developed for the 4K-JT cooler was extended to cover the operating and fluid parameters of the 2K-JT cooler. A summary of the required performance is given in Table 1 and the model has been used to optimise the design of the heat exchangers whilst respecting those criteria. To ease the requirements on the low pressure compressor, a maximum pressure drop has been allowed in the return line. The selected heat exchanger configuration is shown in Table 2.

Table 1. Cooling power requirements.

Requirement	Value
Total heat exchanger system pressure drop	< 50 mbar
Load on the first stage	< 300 mW
Load on the second stage	< 150 mW
JT cooling power	≥ 20 mW @ T≤2 K

Table 2. Selected heat exchanger configuration.

HX	Tube	Gauge	ID [mm]	OD [mm]	Wall [mm]	Length [m]
1	HP	17	1.10	1.47	.185	1
	LP	8	3.28	4.04	.380	1
2	HP	17	1.10	1.47	.185	2.5
	LP	8	3.28	4.04	.380	2.5
3	HP	17	1.10	1.47	.185	2
	LP	10	2.50	3.30	.400	2

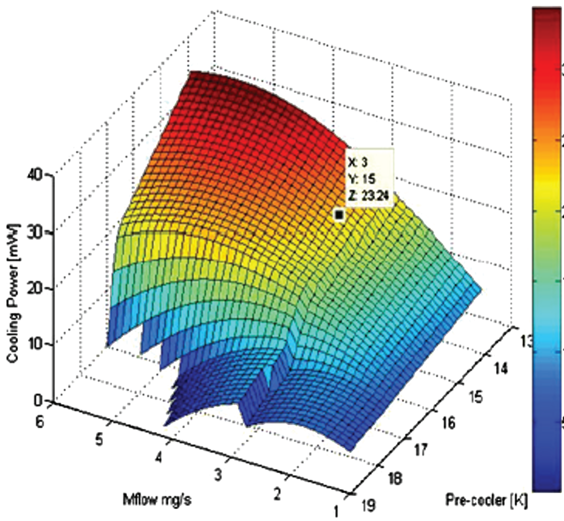

Figure 3. Modelled parameter space for the 2K cooler heat exchanger system.

Table 3. The cooling power parameter space of the selected heat exchanger configuration. Data in the highlighted region meet the design requirements.

	2K stage Cooling power (W)	Mass Flow (mg.s^{-1})								
		2.00	2.25	2.50	2.75	3.00	3.25	3.50	3.75	4.00
High pressure line (Bar$_a$)	6.50	0.0137	0.0153	0.0171	0.0187	0.0201	0.0214	0.0226	0.0237	0.0246
	7.00	0.0146	0.0162	0.0177	0.0198	0.0213	0.0226	0.0239	0.0249	0.0258
	7.50	0.0154	0.0170	0.0185	0.0208	0.0223	0.0237	0.0249	0.0260	0.0269
	8.00	0.0161	0.0178	0.0194	0.0217	0.0232	0.0246	0.0259	0.0269	0.0278
	8.50	0.0168	0.0185	0.0201	0.0225	0.0241	0.0254	0.0267	0.0277	0.0285
	9.00	0.0174	0.0192	0.0207	0.0232	0.0248	0.0262	0.0273	0.0283	0.0291
	9.50	0.0179	0.0197	0.0212	0.0225	0.0254	0.0267	0.0279	0.0288	0.0295
	10.00	0.0184	0.0202	0.0217	0.0230	0.0259	0.0272	0.0283	0.0292	0.0299
	10.50	0.0189	0.0207	0.0222	0.0234	0.0264	0.0277	0.0288	0.0296	0.0303
	11.00	0.0193	0.0211	0.0226	0.0238	0.0269	0.0281	0.0292	0.0300	0.0306

With a nominal high pressure of 8 bar, a plot of the cooling power as a function of mass flow and pre-cooler temperature is shown in Figure 3. Calculations indicate a diminishing return in cooling power for an increasing inlet pressure beyond 8-10 bar. For a given heat exchanger geometry the changes in the operating parameters do not always satisfy the operating criteria. To illustrate this, the cooling power of the selected heat exchanger, for a fixed pre-cooling temperature of 15 K, is shown in Table 3 as a function of inlet pressure and mass flow.

The requirements for the compressor assembly derive directly from the outputs of the heat exchanger model; in summary the low pressure return should be less than 150 mbar in order to meet the temperature requirement, and the high pressure supply should be around 8 bar with a mass flow in the region 2-4 mg/s in order to meet the cooling power requirement.

COMPRESSOR ASSEMBLY

The compressors are arranged in back-to-back pairs such that the exported vibrations are minimised. This can be done most effectively using identical mechanisms operating at equal stroke amplitudes and with their individual piston diameters tuned to meet resonance conditions for each stage of compression. The compressors have a capacitive position sensor incorporated and are operated under closed loop drive control.

Table 4. Selected compressor configuration and operating parameters.

Compression stages	4
Total mass	8.5 kg including baseplate
size envelope	300 mm x 400 mm x 100 mm
operating frequency	45-55 Hz
Input power	<100 W

Each pair is supported directly from a central mount, providing an alignment interface and acting as a heat spreader. The reed valves and buffer volumes are arranged within the mount. This configuration is more compact than the Planck 4K-JT cooler, allows a better axial alignment, and allows more effective heat transfer to the spacecraft panel.

Compressor Modelling

A model has been developed for combined operation of the compressor and reed valve assembly, including compression chamber heat transfer and clearance seal leakage, valve conduction and valve leakage. A wide range of compressor architectures and configurations were modelled, the most efficient configuration was found to be four stages of compression with each stage being a single ended piston acting into an external buffer volume. The model was used to investigate the sensitivities to design parameters. At low pressures valve operation is shown as being critical; in particular the reed thickness should be minimised whilst respecting flatness and reliability considerations, as well as the response time with respect to the operating frequency. In addition, pressure drop and dead volumes associated with the valve housing entrance and exit channels must be carefully minimised. At high pressures, the model shows that piston clearance seal leakage is the major concern.

The model is used in conjunction with a kinematic model that incorporates the motor electrical characteristics to determine piston sizes that minimise the total input power. In general, operation at longer strokes and higher frequencies offer the potential for smaller motor force requirements, but this places conflicting engineering constraints on the flexure spring suspension and motor designs, respectively, and ultimately a trade-off between mass and efficiency considering system level requirements must be made. With that considered, the selected compressor configuration and operating parameters are shown in Table 4.

ANCILLARY PANEL ASSEMBLY AND GAS CLEANLINESS CONSIDERATIONS

The ancillary panel houses gas handling and measuring elements comprising: disconnection valves, particulate filters, a reactive getter, a mass flowmeter, and pressure sensors.

JT coolers are susceptible to clogging from impurity condensates at the JT restriction, a rigorous bake, purge and fill procedure is required to guarantee working fluid purity and a decontamination heater may be provided as back-up. The reactive getter provides additional gas cleaning, particularly for those impurities that may evolve from the internal surfaces of the cooler during its lifetime. The Planck 4K-JT cooler employed a hot reactive getter operating at 320 °C, which was large, heavy and consumed 13 W of electrical power. Much smaller ambient temperature getters are now available and are used on the 2K-JT cooler.

The mass flowmeter, in conjunction with the pressure sensors, is provided to give a measure of the cooling power in operation and to diagnose possible clogging. A space qualified commercial version was flown on Planck but this was bulky and heavy. A much smaller bespoke orifice flowmeter, employing a sensitive differential pressure transducer (Kistler 42464A) in the high pressure line, has been developed for the 2K-JT cooler. After calibration with ^{4}He the flow meter has been found to be accurate to a few percent at the flows of interest.

PLANCK 4K-JT COOLER IN-ORBIT RESULTS AND LESSONS LEARNT

Temperature Stability

The 4K-JT cooler on the Planck spacecraft operated for 4.5 years with no interruptions, blockages or issues from just after launch until the spacecraft was retired. The temperature stability over

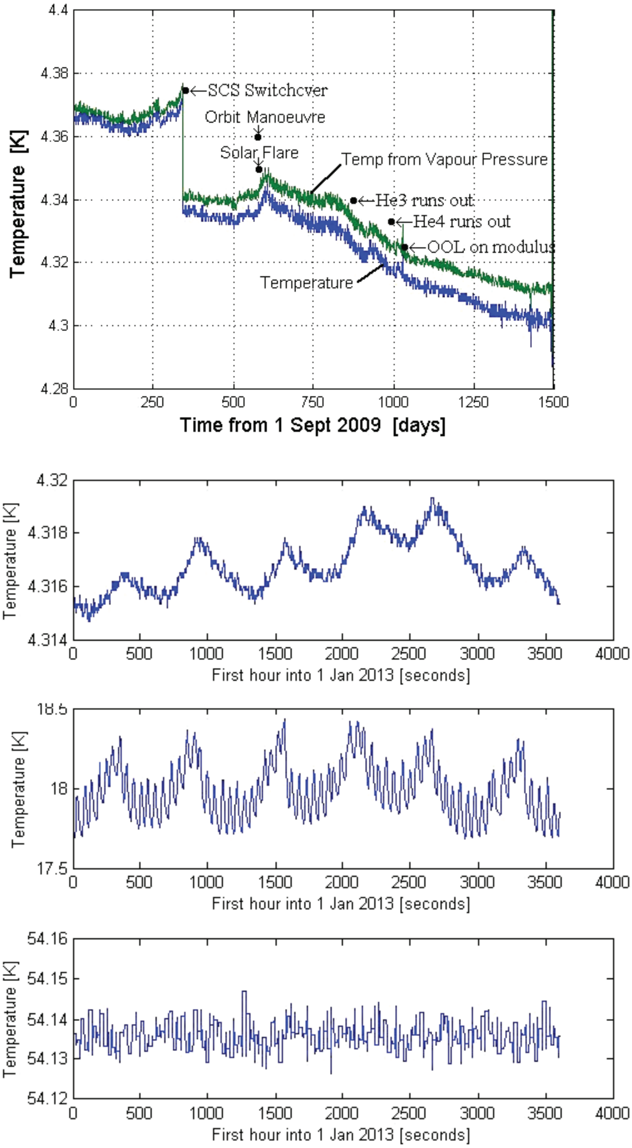

Figure 4. In orbit temperature stability of the Planck 4K-JT cooler.
Top – 4 K temperature vs time from vapour pressure and thermometry.
Bottom – short term fluctuations at 4 K and at the 18 K and 54 K pre-cooling stages.

this period was excellent. Figure 4 shows the temperature measured close to the 4 K interface and also that inferred from the pressure as measured on the ancillary panel as a cross check against sensor drift. Major life events are also shown; the “SCS Switchover” shows the switch from the nominal to redundant 18 K hydrogen sorption pre-cooler, and the two He events refer to the open cycle dilution refrigerator.

Short term fluctuations are well correlated (~2.5 mK/K) with perturbations (~0.6 K, 700 s) of the 18 K pre-cooling stage which are due to sorption bed switching during normal operation.

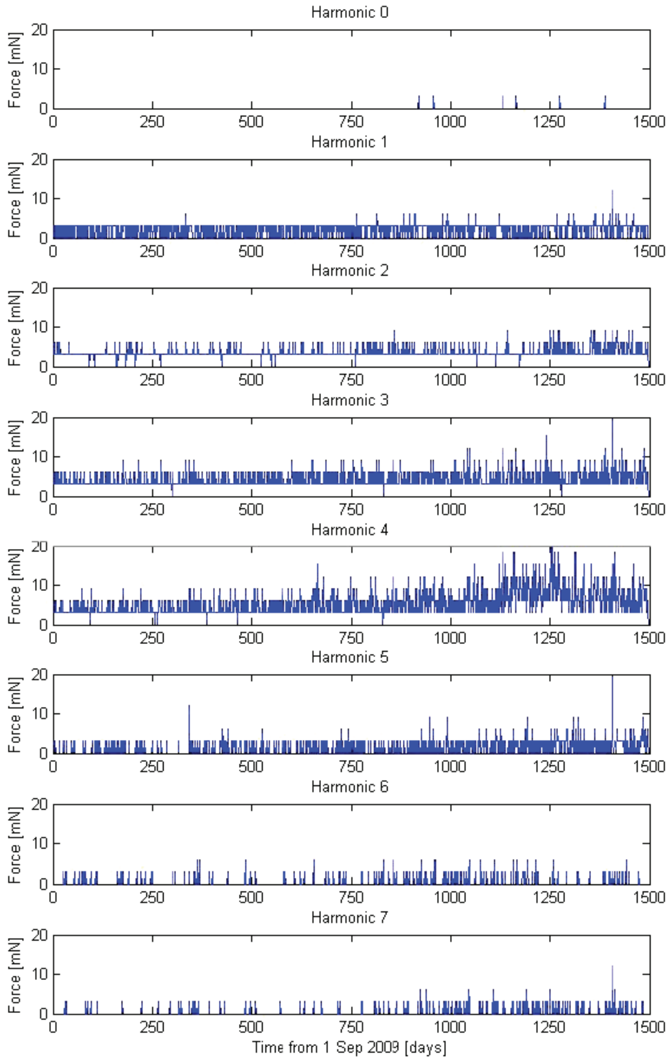

Figure 5. In orbit exported vibrations of the Planck 4K-JT cooler.

Exported Vibrations

The compressors on the Planck 4K-JT cooler were mounted to the spacecraft structure through force transducers. These were part of a closed loop vibration control system and also provided a measurement of the residual vibrations transmitted to the spacecraft structure. The requirement was to reduce the exported forces to less than 40 mN; note that a single uncompensated mechanism generates ~50 N. The harmonic content of the exported force is shown in Figure 5 over a one month period. The measurement is resolution limited at the fundamental frequency, only the occasional switching of a single bit can be seen.

As part of the control algorithm, harmonic corrections are applied to the compressor drive waveforms. The amplitude and phase of these corrections were monitored over the 4.5 year mission duration, it was anticipated that these would evolve as the mechanisms aged. However, this was not found to be the case; instead, only minor changes in the harmonic correction table were observed indicating that there was no age-induced pathology appearing in the mechanisms. This is an interesting and encouraging result for this type of flexure bearing compressor and imparts additional detail to laboratory life testing results.

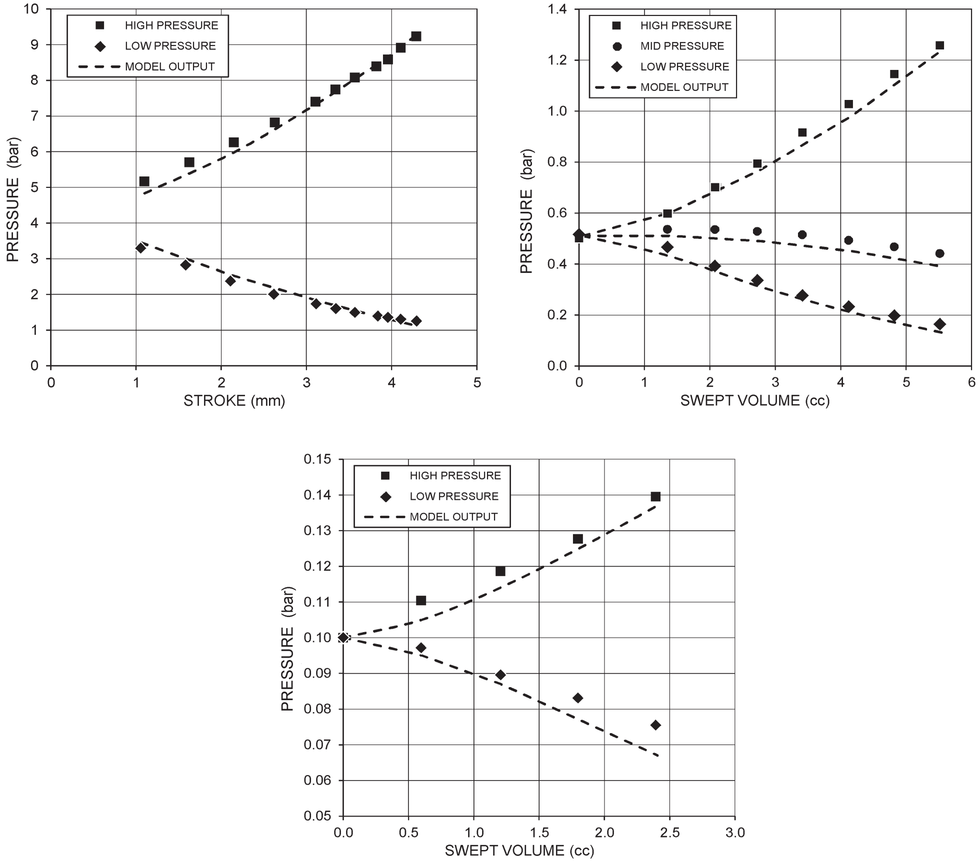

Figure 6. Verification of the 2K-JT compressor and valve model.

Heritage and Lessons Learnt

Many lessons were learnt and heritage was acquired during the development of the Planck 4K-JT cooler that will be taken forward in the development of the 2K-JT cooler. In the context of in-orbit operational experience it is worth highlighting that:

- Exceptional temperature stability over long periods can be obtained provided the compressor amplitude is well controlled.
- Long periods of operation without any evidence of clogging are achievable, despite the use of plastic materials as part of the internal construction and the small orifice size (~12 µm), provided good contamination control procedures are in place.[8] A decontamination heater was supplied on Planck, but was never used.
- No significant changes to the mechanism drive waveforms were required to maintain active vibration control, suggesting no age pathology and that continuous monitoring and vibration control may not always be necessary, depending on mission sensitivity.

2K-JT COOLER BREADBOARD TEST RESULTS

Compressor Breadboard Tests

The 2K-JT cooler compressor and valve model described above was verified by a breadboard test campaign using ^4He in a JT-representative loop and with compressor pairs of several different capacities. Measurements were made over a wide range of operating conditions, results are shown in Figure 6 for operation at different fill pressures most pertinent to the 2K-JT cooler. A needle

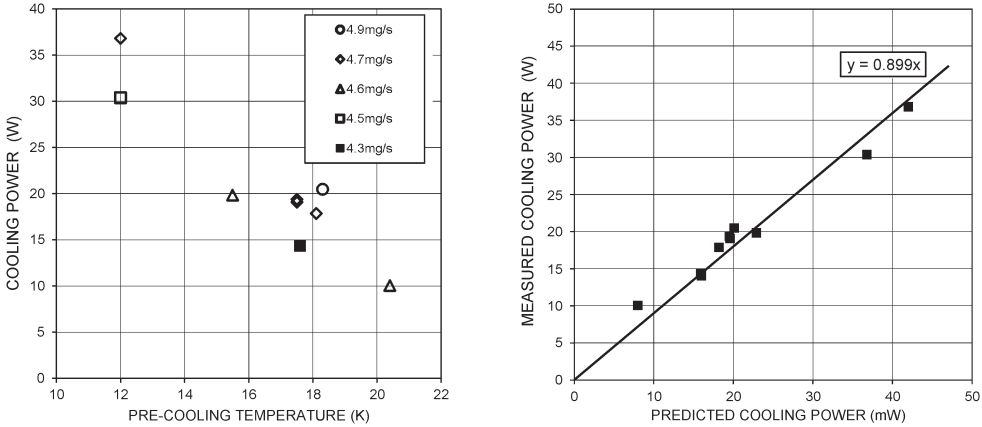

Figure 7. Verification of the 2K-JT heat exchanger assembly.

valve was used as an adjustable orifice. The compressor, reed valve assemblies and the pipework volumes were carefully characterized and those measured parameters were used as inputs to the model. No further adjustments are made as a function of fill pressure, stroke amplitude, or operating frequencies. Measurements were made over a wide range of operating conditions, and results are shown in Figure 6 for operation at the different fill pressures most pertinent to the 2K-JT cooler.

In general, the agreement between the model and the measurements is reasonably good. The most notable discrepancies are at the inlet to the low pressure stage at the lowest operating pressure where the model tends to over-predict the compressor performance. An additional 50 mbar compressor performance margin, in addition to the 50 mbar allowance for the heat exchanger pipework, has therefore been taken when selecting the compressor configuration and operating parameters shown earlier in Table 4.

Heat Exchanger Open Loop Tests

The performance of the selected 2K-JT cooler heat exchanger configuration (see Table 2) has been verified by representative cryogenic tests under thermal vacuum conditions. These early tests were carried out during the compressor set manufacture and were performed in an open loop configuration, using ^4He, with a pressurised cylinder and a commercial scroll pump providing the required pressures at the inlet and outlet, respectively. Pre-cooling was provided by a GM cooler with heaters used to regulate the stage temperatures. Thermal shunts (see Fig. 2) were used to measure the heat rejected at the interfaces.

A JT orifice diameter of 20 μm was selected to provide the nominal flowrate with ^3He. Using ^4He for these tests, flow rates of 4-5 mg/s were typical, dependent upon the high pressure. A temperature of ~3.6 K was achieved at the JT interface, which was limited by the scroll pump performance and its positioning outside the vacuum chamber.

The results of the tests are summarized in Figure 7, which shows the cooling power at ~3.6 K as a function of mass flowrate and second stage pre-cooling temperature. A maximum cooling power of 36.8 mW was achieved with a pre-cooling temperature of 12 K and a mass flow rate of 4.7 mg/s. Also shown in the figure, for the same data, is the measured cooling power against that predicted by the heat exchanger model described above, with ^4He as the working fluid. The agreement is reasonable over the full data range, with the linear fit showing that the model generally under-predicts the cooling power by around 10%. The results give confidence that the heat exchangers will provide the desired performance when under the nominal 2K-JT cooler operating conditions and with ^3He.

CURRENT STATUS AND NEXT STEPS

A Demonstrator Model 2K-JT cooler is under development and is targeted for use on ESA Athena mission. Much of the heritage from the Planck 4K-JT cooler is being carried forward in this development. In particular, the heat exchanger and thermal interface architecture is directly retained. Improvements in technology are being implemented in the compressor and ancillary panel assemblies that will significantly reduce their mass, their size envelope, and their input power requirements.

To date, the performance of the heat exchanger assembly has been measured in a standalone configuration under thermal vacuum conditions. The results are very encouraging and in line with expectations. The ancillary panel was also part of those tests, during which the correct operation of the bespoke mass flowmeter was verified.

At present, the compressor motor modules are undergoing characterisation prior to the compressor final assembly procedure. Once completed the compressor assembly will be integrated with the ancillary panel for performance verification with ^{4}He in a loop configuration incorporating an adjustable needle valve as a JT-orifice. Full system testing with the heat exchanger configuration under thermal vacuum conditions will then be carried out with ^{3}He. Afterward it is planned for the compressor and ancillary panel assembly to undergo thermal cycling and high level sine and random vibration testing.

Subsequent to the Demonstrator Model 2K-JT cooler test campaign, it will be delivered to ESA to be incorporated into a 50 mK cryogenic chain demonstrator as part of the X-IFU instrument consortium development activities.

ACKNOWLEDGMENTS

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