CryoBlue – A Low-Vibration 50 K Stirling Cryocooler

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ABSTRACT

The CryoBlue team, a UK consortium including TAS-itUK, Honeywell Hymatic and The Rutherford Appleton Laboratory, have started the development of a low mass, low vibration 50 K Stirling Cryocooler aimed at Earth observation missions and funded by the European Space Agency.

The CryoBlue team draws on specific strengths, experience and capabilities of its members; RAL have expertise in space cryocooler technology and have developed and supplied a wide range of active cooling systems. Honeywell Hymatic have extensive manufacturing capabilities and an existing range of reciprocating compressors for space applications. TASitUK designed and built the low vibration drive electronics for the Planck 4 K cooler and supported its integration on the successful ESA Planck astronomy spacecraft.

In this paper we present the development status and outline the plans for manufacturing and testing of the CryoBlue Stirling CryoCooler Engineering Model.

INTRODUCTION

Long-life cryogenic cooling continues to be a vital component of many space missions, but particularly those concerned with Earth observation in the infra-red. Several missions in preparation (e.g. Meteosat Third Generation, Metimage) and more under study (e.g. expansion Sentinels) require cooling powers of the order of 3 W at 50 K and development of coolers to answer this need is underway in Europe.[1]

The CryoBlue 50 K Stirling cooler offers a high efficiency solution for the demands of future missions by bringing together flight-proven compressors from Honeywell[2-4] with a coldhead from RAL and drive electronics from TASit-UK, both of which build on the considerable experience of these organisations[5-7] with their respective technologies.

The compressors and coldhead are based around long-life linear motors utilizing flexure bearings. The flexures are designed to operate below the fatigue limit of the material – thereby ensuring long-life – and allow the compressor and displacer pistons to operate with non-contact true clearance seals.

The Cryocooler Unit (CCU) is comprised of three sub-systems (see Figure 1): the Compressor Assembly (CPA), the Cold Head Assembly (CHA) – which together form the Cooler Mechanical Assembly (CMA) – and the Cryocooler Electronics (CCE).

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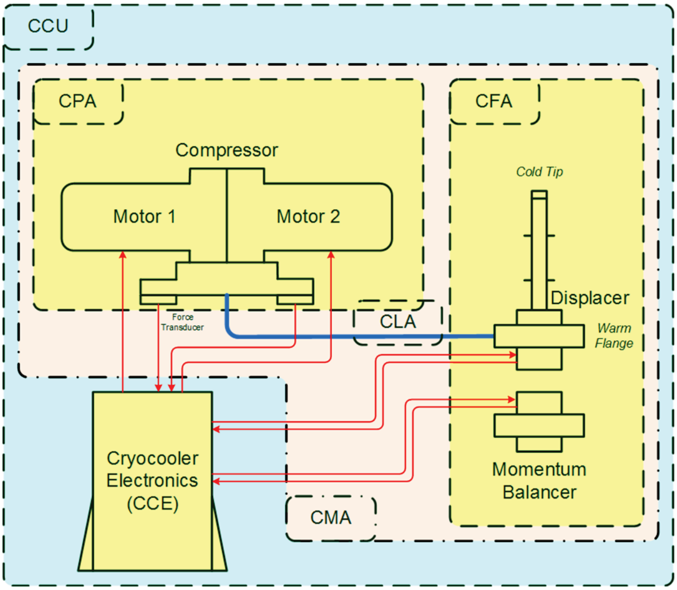

Figure 1. CryoBlue main elements schematic

Table 1. CryoBlue requirements

Requirement	**Value**	**Notes**
Cold tip temperature	50.5 K	
Heat lift (End-of-Life)	2.83 W	= [2 W (user load) + 0.45 W (parasitic load from redundant cooler)] × 1.1 (scatter margin) × 1.05 (end-of-life margin)
Compressor stroke amplitude	< 90% of max.	To achieve thermal performance above (≡ 9.65 mm peak-peak)
CPA & CHA rejection interface temperature	263 K	
Maximum electrical input power to CMA	135 W	
Maximum input power to CCE	160 W	
CCU mass	< 16 kg	Including harnesses, CCE mass < 7 kg
Operating frequency	55 Hz ± 2 Hz	
Cold tip temperature stability	≤ ± 30 mK	over 1 hr (≤ ± 25 mK over 220 s)
Exported vibrations	$< 0.1\ N_{RMS}$	In all axes in 0–600 Hz frequency band
Lifetime	> 10 yrs	Maximum variation of 10% on nominal input over lifetime

PRODUCT SPECIFICATION

The requirements of the CryoBlue cooler are summarized in Table 1. The cooler is designed to deliver 2.83 W at 50.5 K, while rejecting to an interface at 263 K. The cooling power requirement is derived from the need to provide 2 W of useful cooling for the user in addition to the cooling power necessary to handle the parasitic load from an ‘off’ cooler in a cold-redundancy configuration (0.45 W is allocated for this). Margins of 10% (for performance variation between models) and 5% (for end-of-life performance) are applied to the 2.45 W total, which lead to the 2.83 W requirement. The nominal cooling performance shall be achieved at no more than 90% of maximum compressor stroke. This maximum stroke is not set as the stroke permitted by the compressor end-stops, but by the stroke at which the radial spring rate of the flexure reduces to the point where they could allow sufficient radial displacement under gravity to cause contact between the piston and bore.

The maximum electrical input to the CMA to achieve the cooling power requirement is 135 W, with the total input power to the CCE to be kept below 160 W. The nominal operating frequency of the cooler will be 55 Hz, with a nominal fill pressure of 15 bar of helium. The operating frequency has been chosen to ensure the best match between the optimum frequency for performance of the coldhead (which pushes operating frequency down) and the lowest compressor resonant frequency that can be achieved with the largest possible tuning mass. The compressor flexure bearing design remains unchanged – to ensure the high TRL of this element of the system is maintained – meaning that frequency tuning of the compressor design is performed purely through adjustment of the moving mass.

The total mass of the cooler will be less than 13 kg and it will have a lifetime in excess of 10 years, during which the nominal cooling performance should not vary by more than 5%.

The exported vibrations of the cooler shall be less than 0.1 N_{RMS} in all axes. This is achieved through a combination of the active vibration cancellation, performed in the CCE, and mechanism designs that are tailored for low vibration. These aspects are discussed more fully in the following sections.

DESIGN DESCRIPTION

Compressor assembly

The CyroBlue compressor assembly, shown in Figure 2, is a direct close design derivative of the High Efficiency Compressor (HEC) manufactured by Honeywell and subsequently delivered to Northrop Grumman for use in their HEC Cryocooler family. This TRL 9 product has been placed onto multiple platforms, such as OCO-2 and JAMI, resulting in over 200 years of on orbit operation with no failures or change in performance. Other close derivatives of this design have also been delivered and will be utilized on the Mid-Infrared Instrument (MIRI) aboard the James Webb Space Telescope.

The CryoBlue compressor is a fixed-cylinder, moving-piston design utilizing flexure bearings and clearance seals. Two compressor units (or halves) each containing a piston and cylinder are attached to a central center plate and operate co-axially. This compressor maintains its TRL 9 design life of >10yrs continuous operation without degradation within environments of -30°C to +50°C, with an input power up to 180 W. Exported vibration levels are typically <50 mN in the drive axis. It should also be noted that there are no deviations to the well-established proven manufacturing processes and in-process testing that has demonstrated the reliability that the HEC com-

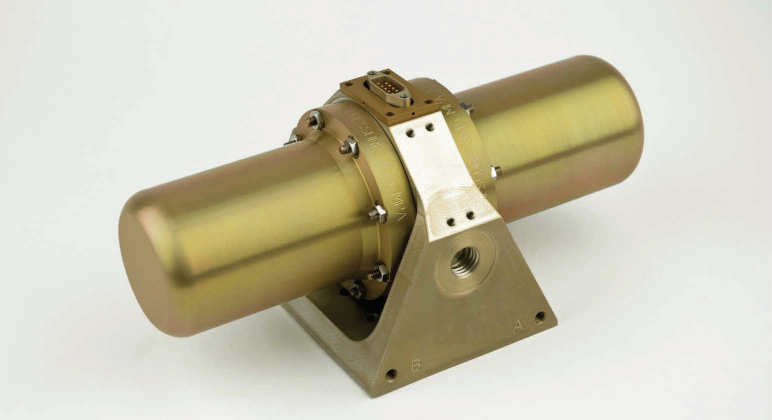

Figure 2. Compressor Assembly (CPA)

pressor has enjoyed over the last 20 years of manufacture, with over 80 compressors delivered to Northrop Grumman.

The compressor assembly consists of two identical compressor halves, accurately aligned on a common centre plate. The CryoBlue compressor assembly uses a bespoke centerplate design which minimizes dead volume in compression space for optimum performance of the Stirling coldhead. As noted above, the moving mass is adjusted to ensure the mechanisms run on resonance at the required operating frequency of 55 Hz.

The seal between the piston and the cylinder is achieved by a true clearance seal. The running surfaces do not touch and attrition wears do not occur. The radial clearance is maintained at 9 to 14 micron to reduce seal blow-by loss and at the same time maintain manufacturability. The linearity and true clearance seal is achieved by mounting the moving piston between two stacks of flexure bearing springs. The springs are designed to operate below the endurance limit of the spring material to ensure infinite life. The spring arm profiles possess high radial stiffness to allow small clearances between piston and cylinder to be maintained under all operating conditions.

The piston is mounted onto a framework which also carries an electrical coil potted on to a coil former. The coil former is supported at each end by the flexure bearing springs described above. The moving coil oscillates in a radial magnetic gap formed by a pair of yokes on the outside and a pair of pole pieces on the inside. Two Neodymium-Boron-Iron (NdBFe) magnets are sandwiched between the pole pieces and the yokes with the magnetizing directions of the two magnets opposing each other thus forcing all the magnetic flux to concentrate at the magnetic gap. This arrangement enhances the driving force of the linear motor. Electrical insulation is ensured by stringent AC and DC insulation testing.

The compressor assembly has a total mass of 3.2 kg and external dimensions of 225×112×102 mm (L×W×H).

Coldhead Assembly

The CryoBlue coldhead has been designed specifically for this program and builds on RAL's long heritage with Stirling coolers. A displacer piston, containing an integral regenerator, is driven by a linear motor mechanism to achieve the correct phase shift between the pressure waves at the warm and cold ends for optimum thermodynamic performance. The design contains several features that address the specific requirements of CryoBlue.

To improve heat rejection from the warm end of the cold finger, the body is machined from aluminium alloy. The cold finger itself is manufactured from titanium alloy grade 5 to minimize thermal conductance from the warm end to the cold tip. Parasitic heat leak down the cold finger is further minimized by machining the titanium tube with a wall thickness of 120 microns. The two parts are joined by laser welding each one to an aluminium-titanium interface piece that is formed by friction welding. The welding process has already been developed and verified on this and other RAL programs.

The aluminium body is a cuboid design with the motor mechanisms and the cold finger mounting to opposite faces (see Figure 3). Of the remaining four faces, one is allocated to pneumatic connections (transfer line, fill port), one is for electrical connections and the remaining two orthogonal faces are available for heat rejection and/or mounting. This design offers considerable flexibility in mounting the cooler on the spacecraft and allows for the possibility to separate the thermal and mechanical mounting interfaces.

A launch support tube is employed to protect the thin-walled cold finger under launch vibrations. The tube is constructed from G10 with aluminium end fittings. Excessive motion of the cold finger is snubbed by PEEK arms, which are fitted to the top of the launch support tube. The arms are sized to leave a small clearance between themselves and the tip of the cold finger (~ 100 microns) when assembled so that no additional parasitic head load is induced by the support tube. Any motion of the cold finger that exceeds this clearance is snubbed by the arms.

Lifetime is ensured through non-contact clearance seals, both between the displacer piston and cold finger bore, and between the displacer shaft and bush seal. This latter seal separates the warm end of the regenerator — which sees the pressure waves generated by the compressor — from the

Figure 3. Coldhead Assembly (CHA)

coldhead backshell in which the fill pressure persists with minimal fluctuations. The use of aluminium alloy for the body has an additional benefit here in that it keeps the bush seal at a lower temperature than would otherwise be possible (with titanium, for example); this widens the operating temperature range for the coldhead by reducing the effects of the difference in thermal expansion between the shaft and bush. In common with the CPA, the clearance seals are maintained by flexure bearing springs operating below the fatigue limit of the material.

To meet the demanding exported vibration requirements of CryoBlue, a moving coil motor architecture is employed. This configuration eliminates radial magnetic forces that arise in moving magnet mechanisms which can lead to off-axis exported vibrations. The coil is wound from square copper wire and potted on a coil former that mounts on the motor shaft. A total of four flexure bearing springs support the moving mass. The coil is contained within an arrangement of NdBFe magnets with soft iron poles pieces that create a radial magnetic field, which is perpendicular to the coil windings. An active balancer mechanism (of the same design as the displacer mechanism) is attached directly to the displacer so that in-axis vibrations can be cancelled. A balancing mass, which is tuned on assembly, is mounted to the balancer to provide accurate momentum compensation of the displacer. Furthermore, the exported torques of the displacer and balancer – resulting from rotational motion of the flexure bearings as the mechanisms stroke – are matched. This is achieved through tuning the moment of inertia of the balancing mass and the design of the balancer flexure bearings (which determine the angular acceleration of the moving mass) such that the torque matches that of the displacer.

Both the displacer and balancer mechanisms incorporate position sensors to allow them to be driven in closed loop control. This is important for maintaining the correct phase with respect to the compressors as well as offering a method to minimize exported vibrations without the need for active cancellation.

Kinematic modeling is performed on the displacer to determine the required spring rate to ensure that the displacer runs on resonance under nominal operating conditions. This informs the spring design, where Finite Element Modelling is employed to predict spring rates and stresses.

The coldhead has a total mass of 1.6 kg and external dimensions of 280×84×84 mm (L×W×H).

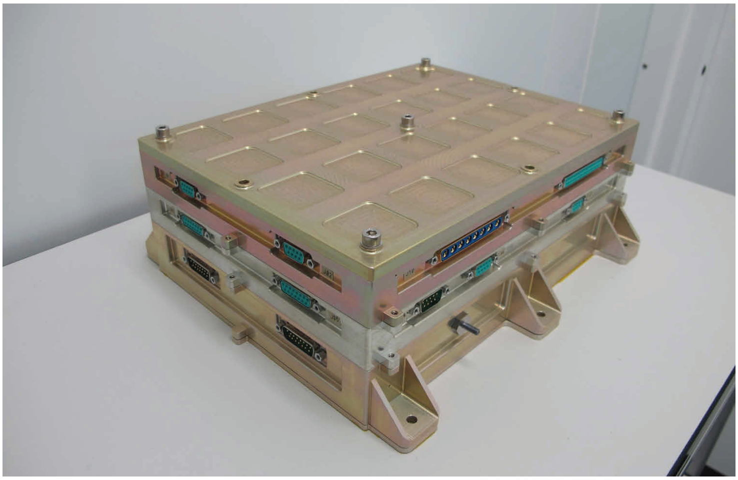

Figure 4. CryoCooler Electronics (CCE)

Cooler Electronics

The CryoCooler Electronics (CCE) is a modular cryocooler drive electronics box consisting of three modules: the Analog Processing Module, which handles data, storage and interfacing, and contains an FPGA and memory; the Cooler Drive Module, which provides mechanism drive and control, including voltage and current monitoring; and the Power Supply Module, which provides the required voltage lines, manages start-up and shutdown, and contains an active line filter to smooth the demand on the spacecraft power supply bus. Two backplanes provide connectivity between the modules.

The CCE is the main interface between the CryoCooler Unit (CCU) and the platform or instrument by providing a MilBus command and control interface and a redundant 28V main input power line. The CCE is designed to provide around 110W compressor input power with a total CCU power consumption of about ~160W. The CCE power supply includes an Active Line Filter to absorb the load variations on the main power bus.

The main functions of the CCE are to provide a command and control management interface via a MilBus interface; a programmable thermal control loop for the Cold Tip; a micro-vibration reduction algorithm for two independent vibration control loops to control the exported vibrations from the CPA and the CHA in order to minimize the exported vibrations at harmonics up to 600Hz; a Launch Lock mode to lock the pistons of both the CPA and CHA; and to provide a data acquisition and processing facility to support the other functions and for inclusion of data in the housekeeping telemetry. The CCE will generate a telemetry packet every second at a data rate of around 3 kbps.

The CCE dimensions are 227×124×102 mm (L×W×H) and has a total mass of 5.1 kg.

PROGRAM STATUS AND NEXT STEPS

The CryoBlue project is in an assembly and test phase for the remainder of 2018. The CPA has been assembled and acceptance tested to demonstrate that the compressor performance is in line with the existing family of the HEC compressors. The CHA is currently in the final stages of assembly with acceptance testing due to commence shortly. The CCE has been assembled and a full set of electrical and functional tests performed to demonstrate compliance with electrical and functional requirements.

System testing is due to commence in the final quarter of 2018. This will begin with cooling performance tests under a range of operating conditions. It will be followed by exported micro-vibration testing. The CMA with then move into thermal vacuum and thermal cycling tests. The CCE will be operating under ambient conditions for these tests and will then undergo a separate thermal vacuum test campaign. The CMA and CCE will also have separate mechanical environment tests, although the CCE will be connected to the CMA for its test to provide launch locking of the mechanisms. Finally, the complete system will come together for life testing in the latter part of 2019.

CONCLUSIONS

A high-efficiency, low vibration Stirling cryocooler is under development by a UK consortium comprising TAS-itUK, STFC-RAL and Honeywell. The cooler is designed to provide 2.83 W of cooling at 50.5 K with a warm rejection temperature of 263 K. This performance is well-suited to the needs of the current and planned Earth observations missions. Testing of the cooler is due to commence at the end of the 2018 and results will be the subject of a future publication.

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