Engineering Model of a High Power Low Temperature Pulse Tube Cryocooler for Space Application

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ABSTRACT

Air Liquide Advanced Technologies (ALAT) has designed, built and commissioned a novel low temperature high power pulse tube cryocooler for space applications. This work was funded by the European Space Agency (ESA) under a Core Technology Program (CTP) in collaboration with Commissariat à l'Energie Atomique (CEA) and Thales TCBV. The cryocooler builds on ALAT commercial LPTC heritage and boosts its performance using a two cold finger configuration with an active phase shifter. The cryocooler provides more than 400 mW at 15K with low level of vibrations and electro-magnetic (EM) emission. The cryocooler passed initial qualification stress tests (temperature, vibrations, vacuum) and is currently at Technological Readiness Level 5 (TRL5).

INTRODUCTION

Previous developments provided ESA programs with single stage pulse tube coolers. They offer reliable, powerful and efficient cooling down to 45K. An example of such a cooler is the Air Liquide Advanced Technology (ALAT) Large Pulse Tube Cooler (LPTC) offering up to 3 W at 50K. Looking forward, Future Earth Observation missions will require cooling well below the 20K mark, to either extend the wavelength range of MCT Infrared detectors or others THz detectors. Ambitious scientific missions aimed at unraveling the mystery of the birth of the universe require cooling sensitive detectors down to the 50mK range or below. In this context our high power low temperature pulse tube cooler will provide the necessary foundation for effective cryochains. It can fulfill multiple roles such as supplying primary cooling to cryogenic shields or providing pre-cooling for helium Joule Thomson (JT) coolers. In particular 2K JT performances are extremely sensitive to heat reject temperature as the Joule Thomson coefficient improves significantly from to 20K down to 15K. Last but not least, achieving cooling capacity in the 20K and below will enable the use of standard superconducting materials. Direct applications can be seen for future electric propulsion systems, plasma confinement magnets, or loss free transmission antennas.

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CRYOCOOLER ARCHITECTURE

Pulse tube cryocooler design and implementation becomes increasingly challenging as the temperature decreases. When applied to the space industry environment further constraints apply with tremendous focus not only on base performance but also on risk management and reliability. Hereafter, it was ALAT's concern to devise the simplest cryocooler achieving the highest thermodynamic performance using as much scientific, technical and manufacturing heritage as possible.

As the temperature decreases, it is a common solution to increase the number of stages and/or cold fingers to improve the thermodynamic efficiency. To mitigate the complexity level we opted for a configuration based on a first single stage cold finger cooling the intermediate heat exchanger of a secondary single stage cold finger, both driven by a common compressor. This arrangement (see Figure 1) allowed us to leverage extensively on our heritage. The first cryofinger is based on the LPTC [1], the second cryofinger is inspired by the previously developed 20K-50K model [2] and the compressor draws on heritage from the LPTC and LPT9710 compressors manufactured by Thales Cryogenics.

The cooler incorporates two breakthrough technologies in space coolers: the use of a novel low temperature regenerator and an active phase shifter for the second stage. The regenerator employs specifically developed materials. An extensive experimental campaign has been carried out to fine tune the regenerator performance at the 15K operating point [3]. Achieving optimal phase angle between the pressure wave and the mass flow has often been a limiting factor in pulse tube efficiency. Not to mention that at low temperature, the phase lag generated by a capillary inertance may be insufficient. Following [4], we have implemented a secondary small compressor as an active phase shifter. The significant performance and reliability gain outweighs the small weight, power and complexity penalties. Not only the phase shift can be arbitrarily set and fine tuned but the amplitude of the expansion stroke can also be chosen. It allows operating the low temperature cold finger as close as possible to its thermodynamics limits.

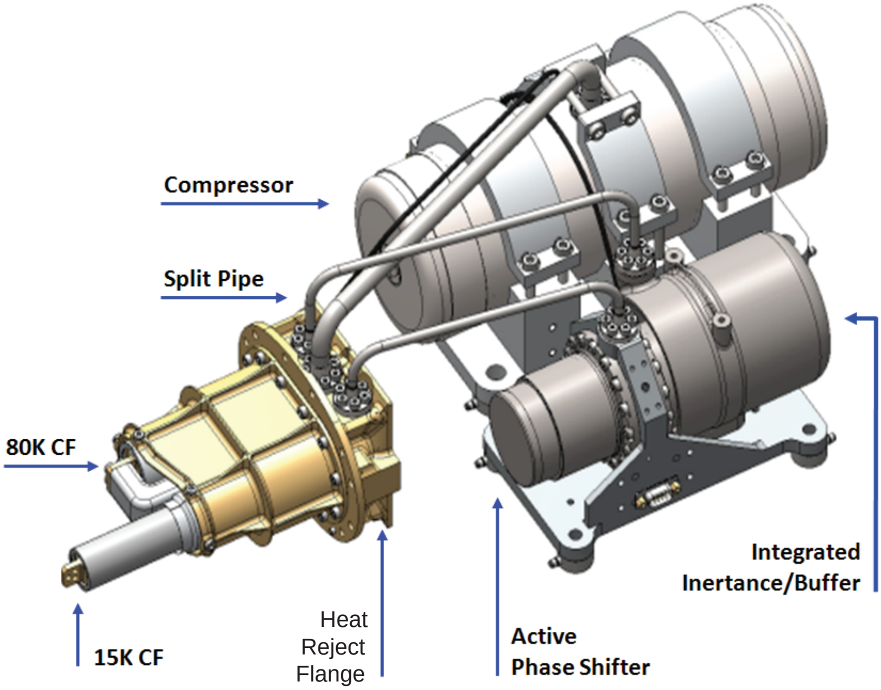

Figure 1. Cryocooler architecture: A common high power compressor drives the assembly of one intermediate single stage cold finger and one low temperature cold finger. The inertance of the intermediate stage is integrated around the active phase shifting miniature compressor for the low temperature finger.

The cooler is compact with a compressor envelope less than 100mm dia. x 300mm and a cold finger unit of less than 100 mm x 150mm x 225mm. The cooler was manufactured using space grade materials and fabrication methods. The compressor and support weigh 12 kg, the active phase shifter 3 kg and the cold finger assembly weighs 2.5 kg. The active phase shift compressor was used for our Miniature Pulse Tube Cooler. It has been commissioned previously and is also at TRL 5.

THERMAL PERFORMANCE

The target core performance of the cooler was to generate maximum power at 15K for efficient pre-cooling of a JT cooler. The unit provides above 400 mW cooling with 300 W electrical input at the compressor. If only limited cooling power is required in an application such as passive detector cooling a base temperature below 10K is accessible. The complete cooling power curve is shown in Figure 2A.

Thanks to the dual cold finger configuration, an additional cooling power of 3.5 W at 90K is also available at the intermediate stage. This feature is particularly interesting for thermalizing primary cryogenics shields for example. The base temperature of the intermediate stage can be as low as 70K. The complete curve is shown in Figure 2B. Lowering the intermediate stage does improve significantly the cooling capacity of the low temperature stage. To this point, we note that the low temperature stage performance is isolated from the warm flange temperature fluctuations as the additional heat load is intercepted by the intermediate stage.

The cooler is naturally stable in temperature as can be seen in Figure 2 D/E showing temperature drift in the course of ~3 h without any active temperature control. < 10 mK/h at the low temperature stage and < 30 mK/h at the intermediate stage is achieved.

If the end application is stringent on weight, the cooler can be operated with a passive phase shifter for the low temperature stage combining an inertance and a double inlet. This configuration was found to be able to reproduce cooling power only slightly lower than with the active phase shifter but cooling capacity reproducibility and temperature and power stability do become a concern. Several technological pathways are foreseen to resolve this limitation. For programmatic reasons it has been decided to use the active phase shifter as the base line.

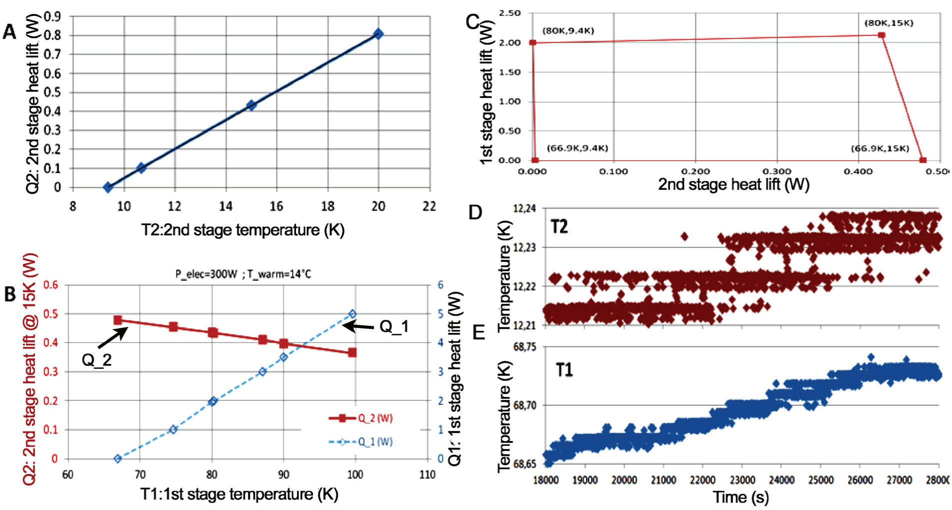

Figure 2. Thermal performance charts: A) Low temperature stage cooling power vs. temperature. B) Cooling power at both stages vs. intermediate stage temperature. C) Cooling power performances map. D/E) Temperature stability of the low and intermediate stage vs time.

EXPORTED ENVIRONMENT INTERFERENCE

Satellite platform, components and sensors are increasingly sensitive to environmental interferences. In particular admissible vibration and electromagnetic levels are reaching ever lower thresholds. Vibrations have direct impact on optical imaging quality. They can affect the satellite pointing accuracy and can also be a source of heating for ultra low temperature scientific missions. EMI level can affect neighboring electronics or add parasitic noise to high sensitivity sensors. Early focus on these environmental performance indicators are essential for the cooler maturation to ensure that potential trade-off against core thermal performances can be implemented if necessary.

The compressor design follows the standard dual opposed pistons design. The symmetric configuration naturally leads to a low vibration levels. The bare compressor is balanced generating less than 5N along the pistons and less than 1.5N off-axis at the driving frequency as seen in Figure 3A/B. Separate control over of the two pistons stroke with an active electronics allows further reduction of the exported vibrations down to the 100mN threshold. The peak at ~25 Hz is generated by the chiller water circulation connected to the warm flange. Note that the active control does not pertain to the off-axis vibrations.

The compressor exports both static and dynamic magnetic field. Leaks in the permanent magnet circuit of the two motors generate a complex 3-D vector field. Figure 4A shows the worst case measurement where a DC field up to 100 µT is found at the compressor face. It decays rapidly after 30 cm. The signal changes sign since it includes both the compressor and terrestrial field which here are of opposite sign. Figure 4C shows the spectrum of the AC field. A series of peaks are found at the driving frequency and its harmonics. The levels are on par with the DC values, ranging from 100µT at the compressor level and decaying below 10uT at 30cm.

ENVIRONMENTAL STRESS TESTING

A spatial cooler must endure intense mechanical, thermal and vacuum stress during the launch phase. The cold finger assembly and the compressor have been submitted to Ariane-like levels:

- 25g sine wave along X, Y and Z from 5Hz up to 100Hz with 2 octaves/minute sweep rate.
- Random excitation 20-100Hz +3dB/Oct, 100-300Hz 0.3 g^2/Hz, 300-2KHz -5 dB/Oct, 12.1g RMS.

The temperature was swept from -50 °C up to +90 °C across two days while the leak rate was monitored with a He leak detector.

The cold finger assembly has a first resonance mode above 180 Hz. The compressor passed also the random test. A passive dissipative resonant launch lock was implemented to reduce pistons motion during launch.

The compressor fully welded construction yields the expected leak free behavior even after the vibration stress test. The compressor was able to operate at -30 °C and +60°C. The cooler did not show any loss of performances after the stress tests.

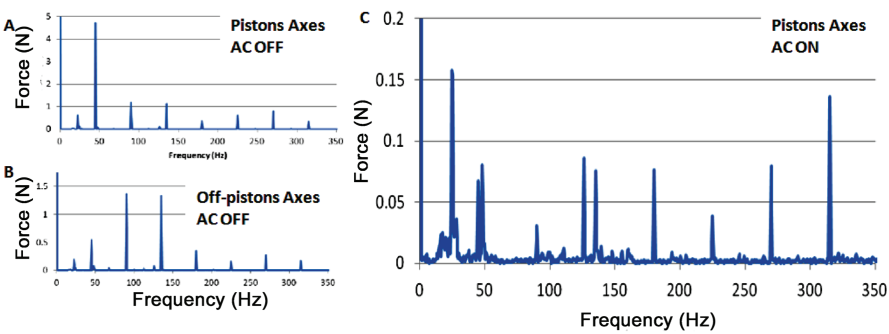

Figure 3. Exported forces from the compressor. Dataset presented on Fig A/B were acquired without active control electronics and show vibrations level in the Newton range. Application of active pistons amplitude and phase control allows reaching <150 mN level along the pistons axis.

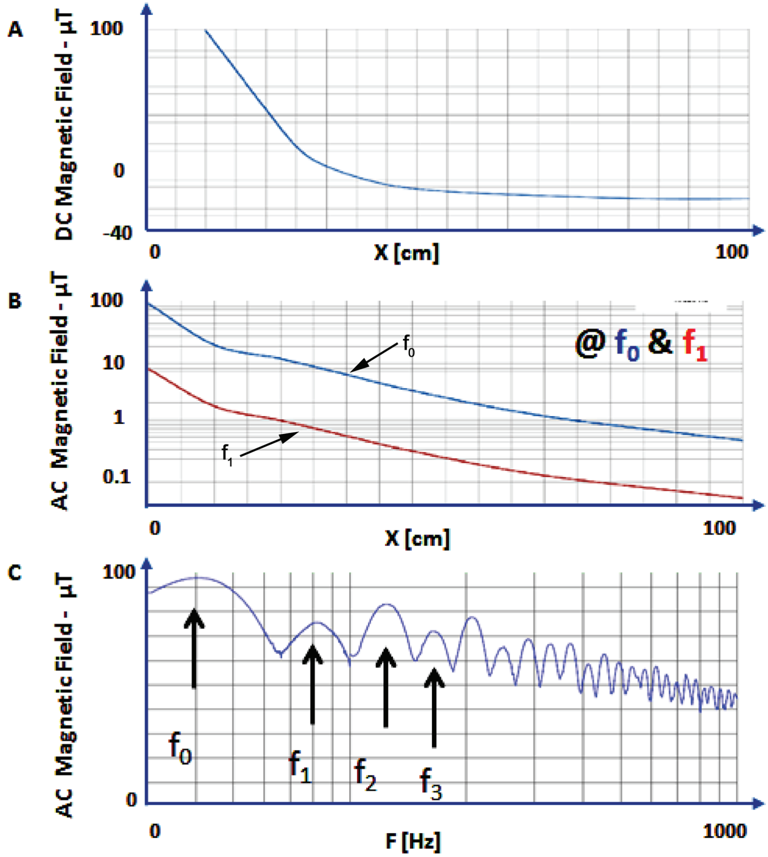

Figure 4. Compressor Exported Electromagnetic Interferences Static A) and dynamic B) vs. distance. C) EMI spectrum tracks the fundamental and harmonics of the motor driving frequency.

PROGRAM STATUS

At this time the cryocooler Engineering Model development is completed: base thermal performances are within the initial scope of work and the preliminary qualification tests have not exposed any major technological limitations.

The cooler is now entering a maturation phase. Several performances improvement pathways are available. Current R&D development in novel regenerator materials are promising. They could allow reducing the base temperature to below 8K or increase the available cooling power up to 25%. The compressor resonant frequency is currently several Hz above the cold finger optimum operating frequency. Improvement in frequency matching between the cold finger and the Compressor will raise the Power Factor and reduce accordingly the Joule losses. Up to 20% improvement in system efficiency may be in reach. Although the cold finger and the compressor are now at TRL 5, standard laboratory hardware was used to commission the unit. The core of the development effort will focus on a dedicated electronics. The new electronics will leverage on the existing standard from the LPTC while improving the modularity of the architecture to match each customer's specific technical and geographical needs while minimizing the budget. This phase will also include a lifetime study. The cooler is designed to sustain more than 10 years of continuous operation as is its LPTC predecessor.

The cooler is on the baseline of the Cryochain for the X-IFU/Athena mission scheduled for launch in 2028. Other candidate missions includes the Cosmic Microwave Background polarization explorer Core +. A flight model could be available as early as 2020.

CONCLUSION

ALAT and its partners designed, manufactured and commissioned a novel high power low temperature Pulse Tube Cryocooler. This campaign has successfully addressed the needs raised in the original scope of work. The cooler offers above 400mW at 15K of cooling power with an additional 5W at 100K in a compact sub 18kg package and 300W of electrical input at compressor level. The cooler generates less than 1.5N forces (sub 0.15N along pistons axis). Static and dynamic EMI levels are below 100µT at the cooler and below 10µT at 30cm. The cooler has undergone preliminary launch vibration and thermal stress tests and is currently rated at Technological Readiness Level 5.

REFERENCES

1. J. Butterworth, G. Aigouy , C. Chassaing, B. Debray and A. Huguet, "Pulse tube coolers for Meteosat Third Generation," *Adv. in Cryogenic Engineering*, Vol. 59, Amer. Institute of Physics, Melville, NY (2014), p. 520.
2. J. Tanchon, , T. Trollier, S. Triqueneaux, A. Ravex, "20–50 K and 40–80 K pulse tube coolers: Two candidates for a low temperature cooling chain", *Cryogenics*, Vol. 50**,** Issue 1 (2010), pp. 55–60.
3. Duval, J. M., I. Charles, J. Butterworth, J. Mullié, and M. Linder. "7K-15K Pulse Tube Cooler for Space," *Cryocoolers 17*, ICC Press, Boulder, CO (2013), pp. 17–23.
4. Charles, I., L. Golanski, A. Gauthier, A. Coynel, and J.M. Duval, "20 K coaxial pulse tube using passive precooling," *Adv. in Cryogenic Engineering*, Vol. 53, Amer. Institute of Physics, Melville, NY (2008), pp. 887–94.