15K Pulse Tube Cooler for Space Missions

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ABSTRACT

Air Liquide is working with ESA, CEA and Thales Cryogenics to design, manufacture and test a 15K Pulse Tube cooler system. This cooler is particularly adapted to the pre-cooling needs of cryogenic chains designed to reach 0.1-0.05K for scientific space missions. For the present project, the required cooler temperature is from 15 to 18K with a cooling power between 0.1 and 0.4 watts. The overall electrical power budget is less than 300W (without the electronics) with a 288K rejection temperature. Significant cooling power at an intermediate temperature (typically 80K – 120K) is also available.

Particular attention is therefore paid to optimizing overall system efficiency. To achieve this low temperature, two cold fingers working in parallel have been integrated on one common warm flange and they are connected to one specially developed high power compressor (240W PV power).

The presented work concerns the 15K cooler design and the expected performance in both analytical simulations and the laboratory tests.

This Pulse Tube Cooler addresses the requirements of space missions where temperatures lower than 20K, cooling power higher than 0.1W, extended continuous operating life time (>5 years), compactness, low mass, and low micro vibration levels are critical.

INTRODUCTION

Air Liquide has been developing pulse tube cryocoolers for space applications since the turn of the century. The Large Pulse Tube Cooler (LPTC: 3-7W cooling @ 50-80K) is currently in the final stages of qualification for the French CSO mission and will also equip the IRS and FCI instruments of the European Meteosat Third Generation satellites.¹ The Miniature Pulse Tube Cooler (MPTC) which was designed to provide 1.5W of cooling at 80K has recently been re-optimized for high efficiency, low power operation at temperatures in the range 150-200K.² Air Liquide also developed and manufactured the 100mK dilution cooler for the Planck CMB survey mission launched in 2009.³

In recent years a number of scientific missions has been proposed which require detector cooling into the millikelvin region.⁴⁻⁸ This is typically performed using a combination of several
passive and/or active cooling stages, each stage providing precooling for the following stage and often additional cooling power for radiation shields and interception of conductive heat loads.

Several cooling chains currently envisaged for future X-ray observatories including SXS aboard ASTRO-H (JAXA) and X-IFU on ATHENA (proposed for the ESA Cosmic Vision L2 mission) include a mechanical 15K cooling stage which is used to precool a helium-3 Joule-Thomson cooler. The final 50mK stage can be provided by a multi-stage Adiabatic Demagnetization Refrigerator (ADR)\(^9\), a hybrid \(^3\)He sorption/ADR\(^10\) or a closed cycle dilution refrigerator.\(^11\) Similar cooling chains will also be required for the proposed COoE and PRISM cosmic microwave background survey missions.

The 15K pulse tube cooler currently under development by Air Liquide, in collaboration with CEA/SBT and Thales Cryogenics BV, was originally intended to address the \(^3\)He JT precooling requirements of the XMS instrument for the IXO mission (predecessor of ATHENA), also providing additional shield cooling capabilities at 15K and below 120K. It was considered as a potential candidate for the proposed EChO mission\(^12\), and is currently under consideration for a European cooling chain to be developed under ESA funding, which could then be implemented for the X-IFU instrument aboard ATHENA.

### 15K PULSE TUBE COOLER DESCRIPTION

Following initial trade-off and breadboarding phases\(^13\), the selected geometry employs a single stage 15K pulse tube cold finger which is thermally intercepted by a second cold finger at a temperature of 100-120K as shown in Figure 1. The cold fingers are mounted on a common warm flange so that only a single mechanical and warm thermal interface is required. Both cold fingers are coupled to a single large compressor (maxi-compressor), as shown in Figure 2, currently under development by Thales Cryogenics.

This configuration makes extensive use of existing heritage including the Large Pulse Tube Cooler (LPTC), for the 100-120K stage, and the Engineering Model 20-50K pulse tube cooler\(^14\) already developed under ESA GSTP funding for the 15K stage.

The LPTC cold finger, although retaining its original mechanical design, has been re-optimized to operate at the same pressure and frequency as the 15K cold finger. The pressure wave phase shift is generated using a slightly modified LPTC inertance/buffer design.

For low temperature pulse tube operation it is difficult to obtain the optimal phase shift parameters using passive means, such as an inertance tube with or without double injection, and

![Figure 1. 15K 2-stage cold head showing thermal link and launch support assemblies](image)
it has been found preferable to use an active phase shifter connected to the warm end of the pulsation tube of the second stage cold finger. This is essentially a small compressor working in reverse (the pistons are excited by the pressure wave) and is analogous to the active displacer of a stirling cooler. Unlike a stirling displacer however, the active phase shifter is not integrated into the cold finger and is therefore not subject to the same thermal and thermomechanical constraints that can lead to limited lifetime and side-load sensitivity of the cold finger as well as the generation of high exported vibration levels. The compressor already developed in the framework of the Miniature Pulse Tube cooler\textsuperscript{15} (ESA, Air Liquide, TCBV, CEA/SBT) is well suited to this purpose. It consists of a dual opposed piston, flexure bearing design similar to the main large compressor, with long lifetime and very low exported vibration.

A new 300W large swept volume maxi-compressor is under development for this cooler, largely based on the heritage of the LPTC and MPTC designs as well as that of terrestrial coolers developed by Thales Cryogenics. An engineering model of this compressor is being manufactured and will be available by November 2014.

A proposed integration architecture for the cooler assembly is shown in Figure 3, including the cold head, compressor, active phase shifter and inertance/buffer sub-assemblies. The Critical Design Review has been passed in early 2014 and an engineering model will be assembled and ready for testing by the end of 2014.
A test campaign has been performed using two existing engineering model cold fingers to verify their behavior when driven by a single common compressor:

- 1st stage (80-120K): Re-optimized EM LPTC cold finger with passive phase shifter
- 2nd stage (15K): EM 20-50K pulse tube cold finger with active phase shifter

The large volume maxi-compressor is represented by two Thales LPT9710 compressors connected in parallel to a common split pipe.

For testing purposes, the 1st stage and 2nd stage cold fingers were mounted separately in the cryostat and connected together via a 250mm long thermal link as shown in Figures 4 and 5. This represents a much lower thermal conductance than that foreseen for the integrated design shown in Figure 1.

Figure 6 shows the cooling power obtained at 15K as a function of the total input electrical power to the compressor. 300mW of cooling power is achieved at the 2nd stage for 290W electrical power. It can be seen that for compressor powers up to 350W there is no sign of saturation, suggesting that higher powers can be achieved if a sufficient pressure wave can be generated.

Owing to the long length and relatively small cross section of the thermal link used for these measurements, a very large temperature difference of ~30K was observed between the LPTC cold tip and the 2nd stage intercept. It is known from earlier measurements that the intercept temperature has very little impact on 2nd stage performance for values below 120K. With a 1.2W additional “user” heat load on the 1st stage interface, we obtained a 1st stage temperature of 80K resulting in an intercept temperature of 110K with 290W electrical power and the second stage at 15K. For the thermal link design which will equip the EM cooler (see Figure 1), the thermal

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**Figure 4.** Coupled 15K + LPTC precooling test setup

**Figure 5.** Coupled 15K + LPTC precooling thermal link
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Figure 7 shows the dependence of the measured re-optimized LPTC cooling power together with the estimated heat load from the intercept of the 2nd stage cold finger, both as a function of temperature for 260W electrical power. The cooling power available to the user for shield cooling etc is the difference between these two contributions (taking into account a temperature difference across the thermal link of ~5K). It is therefore expected that the net cooling power available to the user at this stage will be greater that 4 - 5W @ 100 – 110K for <300W total electrical input power.

CONCLUSION

A 2-stage 15K pulse tube cooler system has been designed, and an engineering model representative of a future flight design is being manufactured. Initial tests using existing
hardware show that the cooler will be able to generate 300mW @ 15K + 5W @ ~100K with 300W electrical input power. It is foreseen to further optimize the performance in a dedicated engineering model to reduce the specific power consumption and to increase the maximum available cooling power at 15K.

The engineering model will be assembled and ready for testing by the end of 2014 with a comprehensive test sequence planned for early 2015.

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References


