Status of Air Liquide Space Pulse Tube Cryocoolers

T. Trollier, J. Tanchon, J. Buquet and A. Ravex

AIR LIQUIDE Advanced Technology Division, AL/DTA
Sassenage, France

ABSTRACT

Air Liquide Advanced Technology Division (AL/DTA) proposes two Pulse Tube cooler systems in the 40-80K temperature range. The Miniature and the Large Pulse Tube Cooler (respectively MPTC and LPTC) qualification and production status are presented. The integration of such Pulse Tube cooler systems in upcoming Earth Observation missions such as Meteosat Third Generation, Sentinel 3, etc., is discussed. The associated Cooler Drive Electronics (CDE) is also an important aspect specifically regarding the active control of the cryocooler during the launch phase and the active reduction of the vibrations induced by the compressor. The CDE design description is presented and, in particular, the FPGA-based solution is discussed.

INTRODUCTION

AL/DTA has extensive cryogenics heritage in the European space industry involving both the ARIANE launcher program and a number of orbital systems in space; for example, the 180K high speed turbo-Brayton MELFI on-board the ISS since July 2006, the 100mK dilution cooler for PLANCK's High Frequency Instrument, and the HERSCHEL helium tanks and thermal links. Building on this heritage, AL/DTA is proposing a complete cryocooler system for future Earth observation missions based on a range of pulse tube cryocoolers and a dedicated CDE. The cryocoolers all feature a split coaxial pulse tube cold finger connected to a dual-opposed-piston flexure-bearing compressor with moving-magnet linear motors.

MINIATURE PULSE TUBE COOLER - MPTC

A coaxial version of the Miniature Pulse Tube Cooler (Figure 1) has been developed during the last two years.[2,3] A batch of three cold fingers has been manufactured with a high quality level based on Air Liquide's Standard Flight Procedures. One MPTC unit is currently running in a lifetest at constant input power since August 2007. The number of accumulated running hours as per April 2008 is 5260 hours. The coldtip temperature and environment temperature records for the cooler are presented in the Figure 2.

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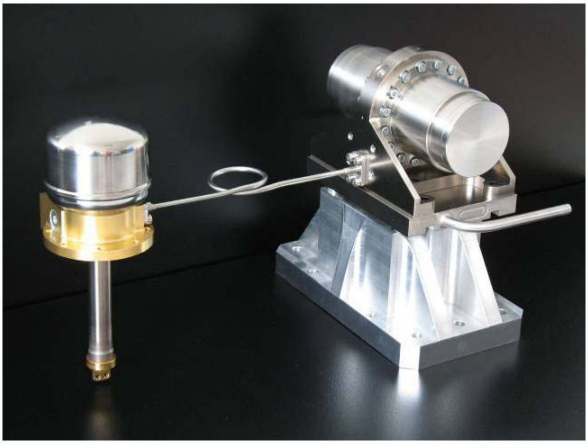


Figure 1. EQM MPTC cold finger and compressor.

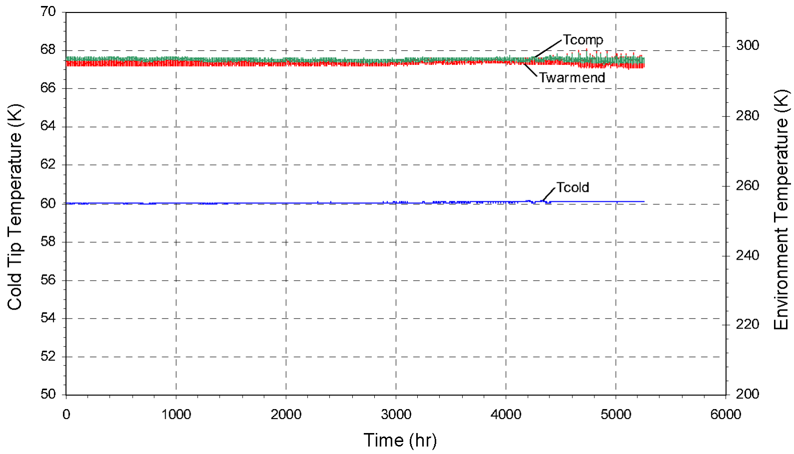


Figure 2. MPTC EQM lifetime test results – started August, 2007.

In April 2008, development and performance tests were conducted to answer a request for quote for ESA's Sentinel-3 mission. The Sentinel-3 mission is one of the low-Earth-orbiting elements of GMES (Global Monitoring for Environment and Security), which responds to the requirements for operational and near-real-time monitoring of ocean, land and ice surfaces over a period of 15 to 20 years. Our technical response for the Sentinel-3 program was based on a complete cryocooler subsystem unit including:

- The cooler itself,
- The cooler drive electronics (CDE) for the thermal management of the cooler, control of its induced vibration, and communication with the spacecraft, etc.
- The thermal link assembly, and the intercooler unit harness and piping.

The cryocooler subsystem architecture was proposed as two "Advanced MPTC" in complete cold redundancy (including CDE) as shown in the Figure 3. This cryocooler has been optimized for 50 W input power to the compressor.

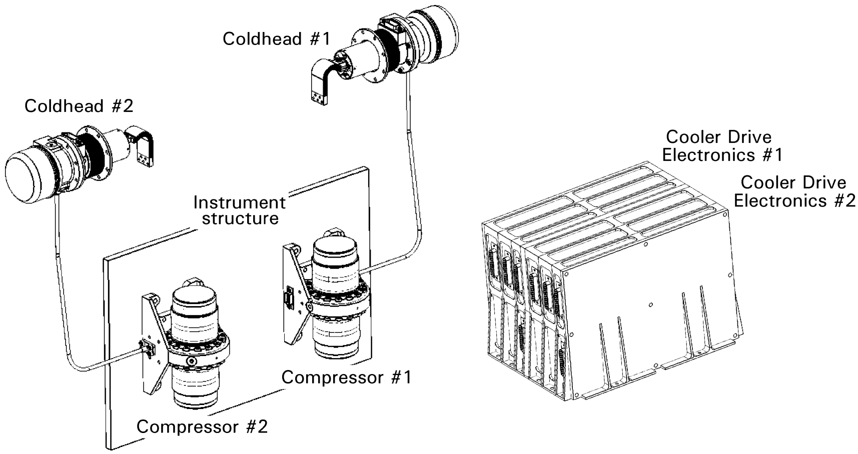


Figure 3. MPTC cooler system unit proposed for ESA's Sentinel-3 project.

The cryogenic performance of the advanced MPTC is reported bellow:

- Cooling capacity: 2480 mW @ 80K
  1610 mW @ 70K
- Rejection temperature: 288 K (both compressor and pulse tube warm end)
- Compressor input power: 50 Wrms

Figure 4 maps the performance of the Advanced MPTC as a function of input power and coldtip temperature for a 288K heat sink condition.

Characterization of the self-induced vibration of the MPTC EQM cooler is reported in Figure 5. As shown, the cold head self-induced vibration has been measured to be bellow 70mN in all axes and in all directions. The RMS value is far bellow 0.1 N throughout the bandwidth required in this program (0-300Hz).

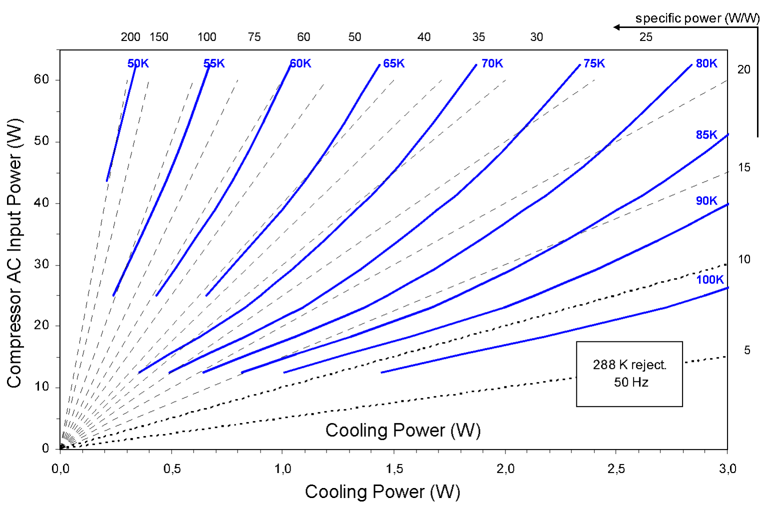
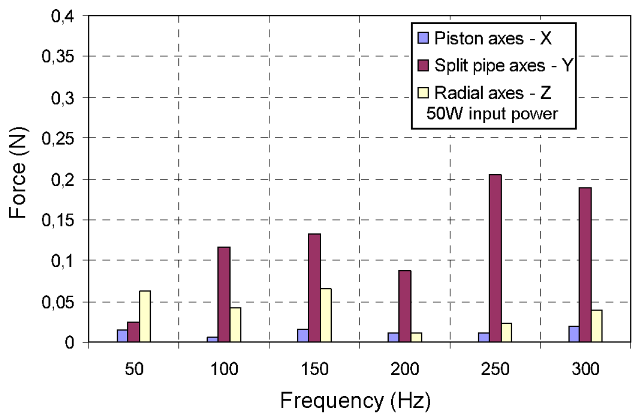


Figure 4. MPTC thermal performance mapping.



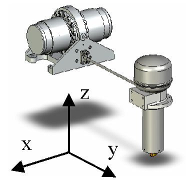


Figure 5. MPTC Self-induced vibration.

LARGE PULSE TUBE COOLER - LPTC

The successful development of the Miniature Pulse Tube Cooler MPTC was driven by the need to cool detector arrays at 80 K. In the meantime, there is a need for Earth Observation to cool Thermal Infrared detectors below 60 K. At these temperatures, the cooling power of the MPTC, or the space qualified 50-80 K Stirling cooler from EADS-Astrium UK Ltd, is marginal or not sufficient. In order to provide European coolers for the temperature range of 40-60 K, a large heat lift Pulse Tube Cooler LPTC is required in addition to the MPTC.

An Engineering Model (EM) of the LPTC has been designed, manufactured and tested in partnership with AL/DTA, CEA/SBT and THALES Cryogenics BV in the framework of ESA/ESTEC contract 18433/04/NL/AR.[1] The EM (S/N001) performance was 2.3W cooling power lifted at 50K with 160W electrical input power to the compressor and 283K temperature rejection.[2] The EM was successfully tested to thermal and mechanical loads at qualification and duration levels.

Currently, four Engineering Qualification Models (EQM) are under production for various projects and an illustration of the EQM S/N002 is attached in the Figure 6. Photos of the integration of the LPTC EQM S/N002 on a cryostat mock-up at Thales Alenia Space premises are attached in Figure 7.

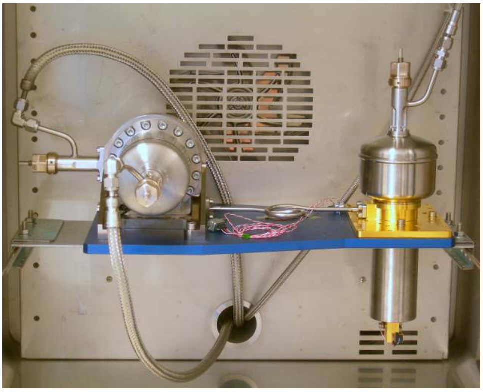


Figure 6. LPTC EQM S/N002 during curing/filling process.

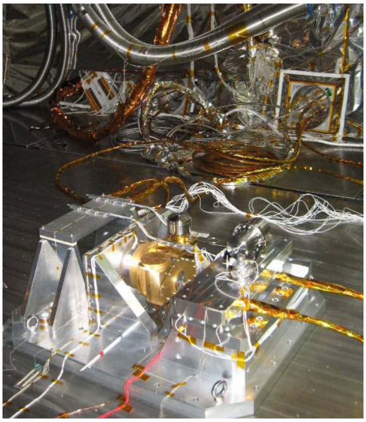


Figure 7. LPTC EQM S/N002 integrated on a cryostat mock-up and vacuum chamber (courtesy of ThalesAlenia Space)

In addition to thermal performance, the output forces of the LPTC EQM S/N002 have been measured on a dedicated test bench placed on a seismic block. The output forces at the compressor and cold finger warm end interfaces are measured separately in 3 axes over a 1 kHz bandwidth during cryogenic operation with controlled temperature interfaces (chilled water). The output force profile measured on the compressor piston axis (driving axis) is reported in Figure 8 for 80 Wac input power applied to each compressor coil (160 W total compressor). At the fundamental driving frequency, the output force is measured at less than 0.6 N, and all other harmonic levels are measured below 0.25 N up to 1 kHz.

Figure 9 illustrates the capability of the Cooler Drive Electronics (CDE) to reduce the output force levels once activated. The two coils of the compressor are then supplied separately (master & slave) with input voltage controlled over the fundamental and seven harmonics. As shown, the output force level is drastically reduced over the controlled frequency bandwidth. For the fundamental, the level is reduced down to 25 mN. Notice that for frequencies above 400 Hz, the level is not changed with and without active vibration control because of the limited frequency harmonics contained in the control signal.

Two of the LPTC EQM coolers (S/N003 to S/N005) will be submitted to thermal and mechanical qualification testing prior to being run on a dedicated endurance test bench.

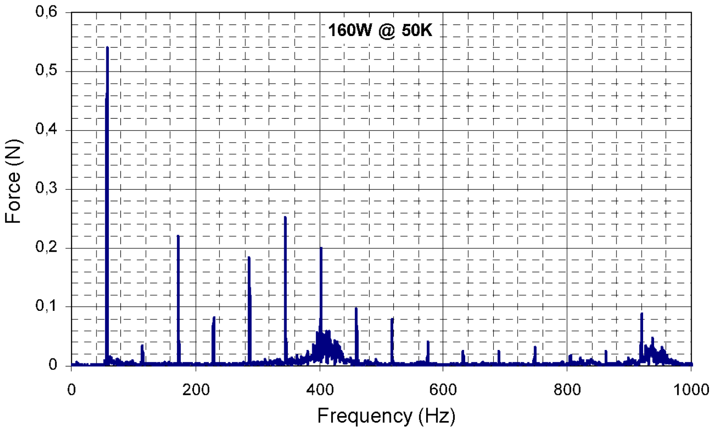


Figure 8. LPTC compressor axis output forces WITHOUT active cancellation.

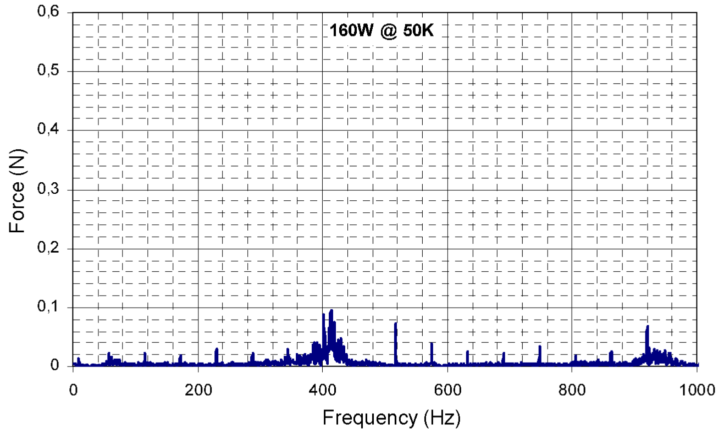


Figure 9. LPTC compressor axis output forces WITH active cancellation.

COOLER DRIVE ELECTRONICS - CDE

The architecture of the CDE developed by Air Liquide in partnership with CAEN Aerospace (refer to CDE overall block diagram reported in the Figure 11) is composed of three separated boards that implement the following functions:

- The DC/DC converter board,
- The power board,
- The control board.

DC/DC converter board

This board is directly connected to the primary power bus and provides the DC voltages required by all the other blocks inside the CDE. It hosts the EMI filter, a boost pre-regulator, and a push-pull isolated DC/DC converter. A couple of thermistors, placed at the hottest point of the board, provide temperature telemetry to the satellite, together with power-bus supply current and voltage telemetry. Analog telemetry proportional to the main DC/DC converter output voltage is also provided. CDE primary power bus voltage conditioning is implemented by a DC/DC converter board that houses the following functional blocks:

- EMI input filter to cope with conducted emissions and susceptibility EMC requirements.
- Boost pre-regulator stage. This block acts as an active filter that shall attenuate below specified limits the low frequency sinusoidal current components absorbed by the class D amplifiers driving the compressor coils.
- Push pull converter. This block is an isolated DC/DC converter that provides all DC voltages to the other blocks inside the CDE.
- Two temperature sensors—one to be interfaced with satellite nominal side, and one with satellite redundant side—will be used to monitor the temperature in the hottest point of the board (near primary switching MOSFets and PWM controller).
- Power consumption monitor. Two analog telemetries (one for input voltage and one for input current) will be provided to monitor the CDE power consumption. Since these signals need to be electrically isolated from the power lines, a linear optocoupler will be used to transfer the signal.

Input overcurrent/shortcircuit protection is usually provided to the instrument via an external 5A Latching Current Limiter.

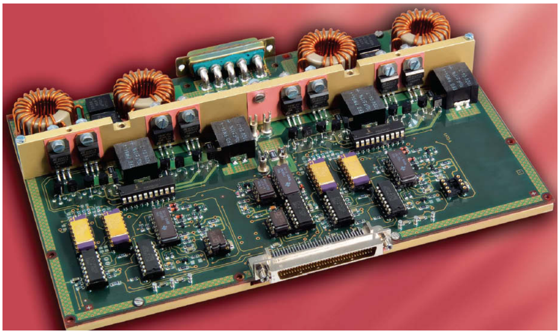


Figure 10. EM power board of the CDE.

Power Board

This board (Figure 10) houses two identical and independent class-D amplifiers that are used to drive, respectively, the master coil and slave coil (used for vibration reduction). Two couples of temperature monitors are sent to satellite telemetry to switch off the unit in the case of a failure that generates an increased power dissipation. Each amplifier provides one output voltage monitor that is an attenuated replica of the output voltage and one current monitor that is a replica of the output current. An additional thermistor for each amplifier, together with output voltage and current monitors, are sent to an analog protection circuit that switches-off both amplifiers in case of over current, over voltage, over temperature, or output current mismatch between the master and slave. A flag with the relevant fault condition is sent to the control board to communicate to the instrument the type of failure that has occurred.

Control Board

This board contains an FPGA for temperature control, ADCs for control and sinusoidal signal generation, ADCs and MUXs (and relative signals conditioning circuits) for external and internal sensor readout and for readout of CDE input and output voltages, and a RAM for storage of acquired parameters. In particular, the Processing Unit provides the following features:

- Sinusoidal signal generation for both Master and Slave,
- Acquisition of the force transducer sensors (load washers),
- Acquisition of external thermal sensors,
- Acquisition of output signals voltage and current,
- Cold-tip temperature control loop,
- Vibration Reduction Control,
- Communication to external instrument I/F via RS-422 interface,
- Management of direct digital lines from/to CPE,
- Management of Synchronization signals from instrument,
- Management of EQSOL lines from satellite IF,

The logic leading to the selection of the FPGA solution are summarized below:

- Components number: the large front-end interface for the needed sensors/controls should require the utilization of a companion small FPGA also in case of a micro-programmed solutions (plus an external SRAM to store its run-time program and data).
- Effective re-programmability requirements: since the control board is targeted for only a specific application, the complete system re-programmability is not really required.
- Multi-tread issues: the problem to be afforded is composed of several tasks to be accomplished in parallel. The single task does not present a large numeric complexity, but the need to keep synchronism among all of them is the major challenge of this application.

SUMMARY

Air Liquide's MPTC and LPTC pulse tube coolers, including their CDE with vibration cancellation (Figure 11), are now available for Earth observation applications. These two products clearly represent a technology advance and integration advantage compared to the former Stirling technology used in the past, mainly in Europe.

A companion paper[4] at this conference describes a third cooler product that is under development to provide a 15-20 K pulse tube pre-cooling stage as an alternative to two-stage Stirling coolers.

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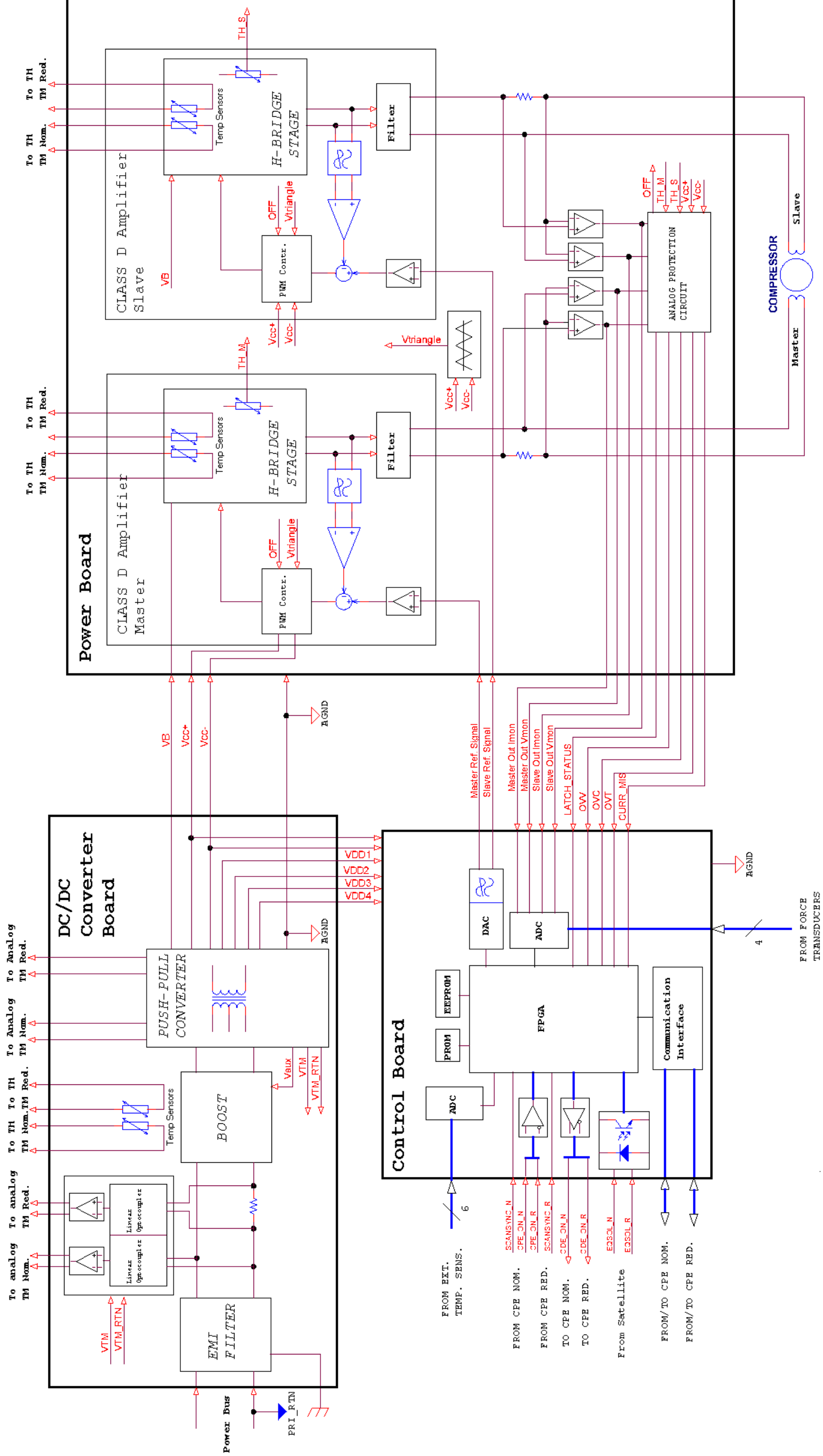

Figure 11. CDE overall block diagram.