150K - 200K Pulse Tube Cooler for Micro Satellites

C. Chassaing[1], J. Butterworth[1], G. Aigouy[1], A. Gardelein[1], C. Daniel[2], A. Certain[3], E. Duvivier[3]

[1] Air Liquide, Sassenage, France
[2] Centre National D'Etudes Spatiales (CNES), Toulouse, France
[3] STEEL Electronique, Martres Tolosane, France

ABSTRACT

Air Liquide has been working with the CNES and Steel Electronique during 2013 and 2014 to design, manufacture and test a Pulse Tube cooler to cool infrared detectors for microsatellite missions. The cooler is particularly well adapted to the needs of the CNES MICROCARB mission to study atmospheric Carbon Dioxide which presents absorption lines in the near infrared, at 1.6 μm and 2.0 μm. The required cooler temperature is from 150 to 200K with a cooling power between 1 and 3 watts. The overall electrical power budget including electronics is less than 20W with a 288-300K rejection temperature.

Particular attention is therefore paid to optimizing overall system efficiency. The microvibration and thermal control systems already developed for the AL-AT Large Pulse Tube Cooler have been implemented into a new low power electronics architecture. The presented work concerns the new cold finger and electronics test results. The cooler uses the compressor already developed for the 80K Miniature Pulse Tube Cryocooler. This Pulse Tube Cooler addresses the requirements of space missions where extended continuous operating life time (>5 years), low mass, and low micro vibration levels are critical.

INTRODUCTION

Air Liquide began its first developments on pulse tube coolers in the mid nineteen nineties for military applications and began working on space cryocoolers around the turn of the century. The company has developed during the last ten years some highly reliable and efficient cryocooler systems which it is supplying for the French CSO and European Meteosat Third Generation space missions.[1]

The Miniature Pulse Tube Cooler (MPTC) was the first pulse tube developed by Air Liquide specifically for space applications, initially in the framework of an ESA TRP contract [2], before being optimized and matured under internal R&D funding.[3] The MPTC was designed primarily to produce 1 to 1.5W of cooling power in the 60 – 80K temperature range.

In 2011 a need was expressed by the CNES (French National Space Agency) for a small cooler with low mass and requiring very limited electrical power. The requirement was to cool infrared detectors in the 150-200K range for micro-satellite missions.[4]

Cryocoolers 18, edited by S.D. Miller and R.G. Ross, Jr.

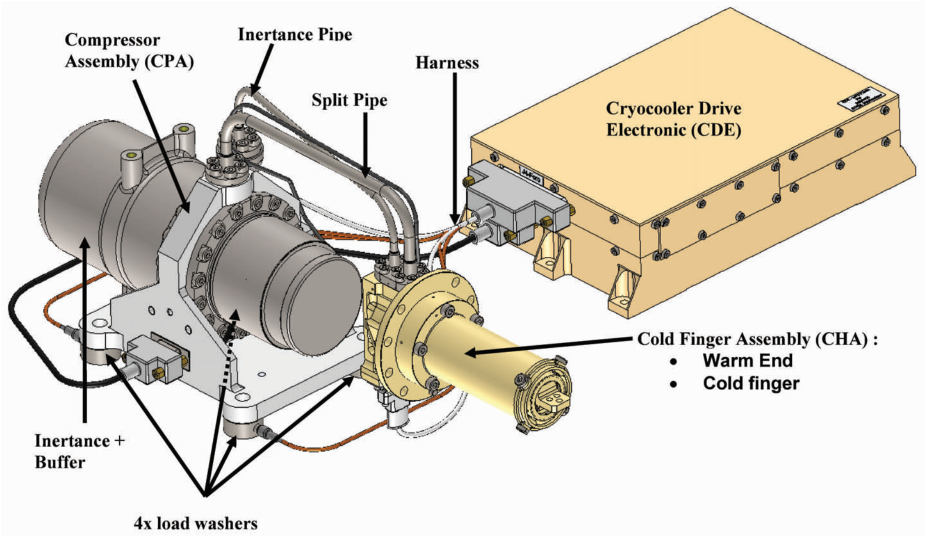

Figure 1. 150-200K Miniature Pulse Tube Cooler System

To limit the development effort and to take advantage of existing hardware and heritage, it was proposed to modify the MPTC cold head design to optimize its performance at higher temperatures and low input power and to integrate design improvements already implemented on the LPTC cooler for the CSO and MTG programs. In parallel, a new, high efficiency Cooler Drive Electronics (CDE) has been developed. The MPTC compressor is re-used without any modification.

The main objective of this cooler is to provide 1 to 3W cooling power within the 150-200K temperature range with an high efficiency to limit the total electric power consumption to 20W including the electronics.

150-200K MINIATURE COOLER DESCRIPTION

The pulse tube technology on which the design is based has no moving parts inside the Cold Head Assembly. This solution limits the exported micro vibrations and increases reliability compared to the Stirling displacer technology.

The cooling system, shown in Figure 1, is composed of a Compressor, a Cold Head Assembly and a Cooler Drive Electronics.

The Compressor Assembly

The Compressor Part Assembly (CPA), shown in Figure 2, is composed of two head-to-head pistons connected to a single compression chamber (dual opposed pistons), within a compact assembly optimized to limit the induced vibrations. The pistons are supported by two flexure bearing packs located at the front and at the rear of the piston. The pistons are driven by linear moving magnet motors. The mounting system provides high radial stiffness and allows only translation along the piston/cylinder axis over a wide range of piston amplitudes and radial mechanical loads. The high reliability and long lifetime is mainly ensured by the absence of contact between piston and cylinder which eliminates this major cause of wear. Moreover, the coils are placed outside of the working fluid, eliminating the main contamination source of the helium and the need for gas-tight electrical feedthroughs. The static coil design also suppresses the risk of failure due to rupture of flying lead connections.

Finally, the only components in the design that are subjected to fatigue are the flexure springs that suspend the pistons. Careful design ensures that these flexures are subjected to a stress well below their high cycle fatigue threshold thus ensuring very long lifetime.

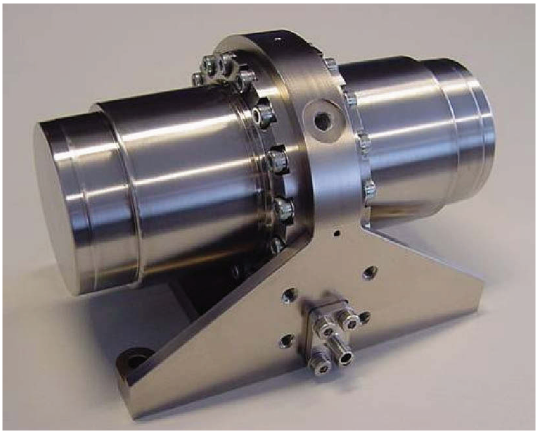

Figure 2. MPTC dual piston compressor manufactured by Thales Cryogenics BV

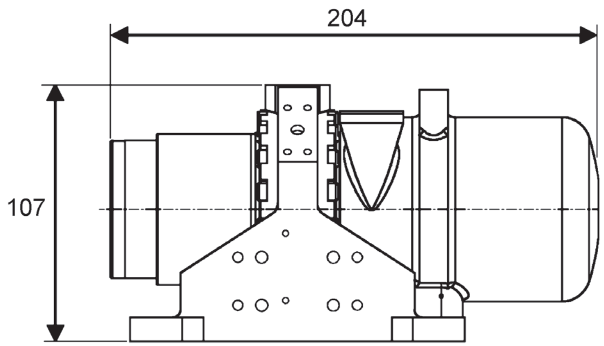

Figure 3. Compressor layout with inertance and buffer assembly

The Buffer and Inertance Assembly

The buffer is mounted around one half of the compressor. The buffer is “self-contained” and mounted onto the compressor baseplate (see Figure 3). It is made of an inner and an outer shell, both in titanium alloy which are shrink fitted and welded together. The inertance is contained within the buffer assembly.

The Cold Head Assembly

The Cold Head Assembly (CHA) contains no moving parts. All the materials are metallic and the helium enclosure is metal sealed to ensure robustness and reliability. The warm end provides the mechanical and the thermal interfaces between the cold head and the detector enclosure. An active cold shield reduces the thermal radiative exchange and the launch support tube protects the cold finger during the launch phase (Figure 4).

The CHA is based on a coaxial configuration to facilitate integration compared to in-line or U-shape pulse tubes. This configuration offers advantages in terms of mass, reliability and simplicity, which makes it attractive for space applications.

The warm flange sub-assembly is composed of an aluminium alloy flange and heat exchangers. The warm flange includes the heat rejection zone for conductive heat sinking.

A titanium alloy launch support tube is used to sustain the high mechanical loads during launch. The proposed design suppresses any lateral motion of the cold tip for maximal robustness and suppresses any risk of shock that can occur when using snubbers. During operation, thermal con-

Figure 4. EM Cold Head Assembly showing warm flange interface and launch support

traction of the cold tip ensures that thermal contact and therefore parasitic heat loads are minimized.

Cooler Drive Electronics

To power the MPTC compressor, to regulate precisely the cold temperature and to reduce exported micro vibrations along the compressor piston axis, a dedicated Cooler Drive Electronics (CDE) has been studied and an Engineering Model has been manufactured and tested:

Architecture: The CDE drives the two compressor coils, in a master and slave configuration. Feedback from temperature and force sensors are used to adjust the master and slave drive signals to regulate the cold interface temperature and to minimize exported microvibrations.

The CDE is designed to operate from a 20-40V BNR (non-regulated power bus) and communicates with the spacecraft through the UART RS422 protocol.

To achieve low electrical power consumption of the logic circuits of the MPTC CDE, a new controller architecture has been selected. This requires less power than classical controller architectures, using for example FPGAs, and is able to manage the necessary functions of the MPTC including the active micro vibration reduction and temperature control algorithms. The CDE has been designed and manufactured by STEEL électronique and is shown in Figure 5.

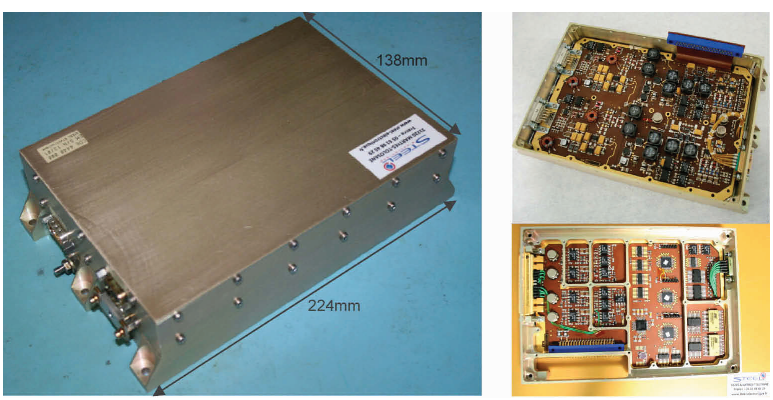

Figure 5. Cooler Drive Electronics (CDE) with the control and the power boards

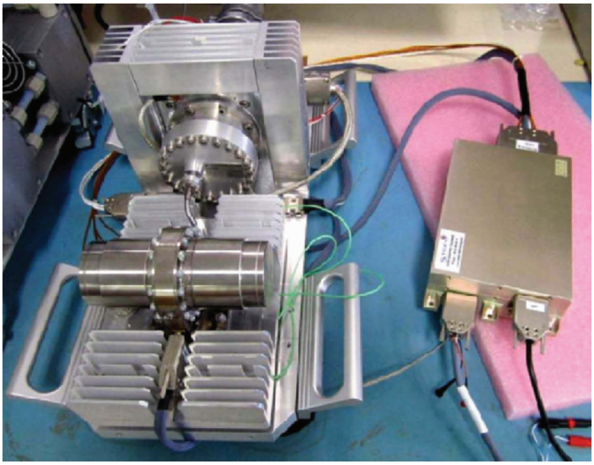

Figure 6. Cooler Drive Electronics (CDE) under test with MPTC

Launch Lock System: Passive relays are integrated to short circuit the 2 coils (master and slave) of the compressor for the launch phase of the mission. This guarantees that there will be no contact between the pistons and the end stops due to the launch vibrations without requiring the system to be powered up during this phase.

Active Microvibration Reduction System: The Cooler Drive Electronics (CDE) implements a closed loop control system and an algorithm to reduce the micro vibrations of the first eight harmonics. Feedback from force sensors located at the compressor mechanical interface is used to calculate the appropriate harmonic corrections which need to be injected into the slave coil in order to minimize the exported vibrations (<0.1N in all axes). The algorithm employed comes from the LPTC heritage.

TESTING OF THE COOLER AND CDE

CDE Tests

Initial testing of the CDE was performed using one of the original 80K MPTCs as shown in Figure 6.

Performance in power and temperature regulation was assessed as well as the vibration reduction functions. Rapid convergence of the temperature regulation loop was observed and the target of the ±10mK stability was demonstrated (see Figure 7).

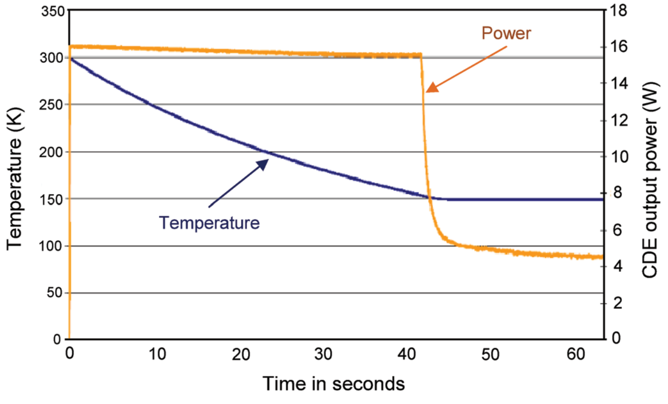

Figure 7. Temperature regulation mode @ 150K

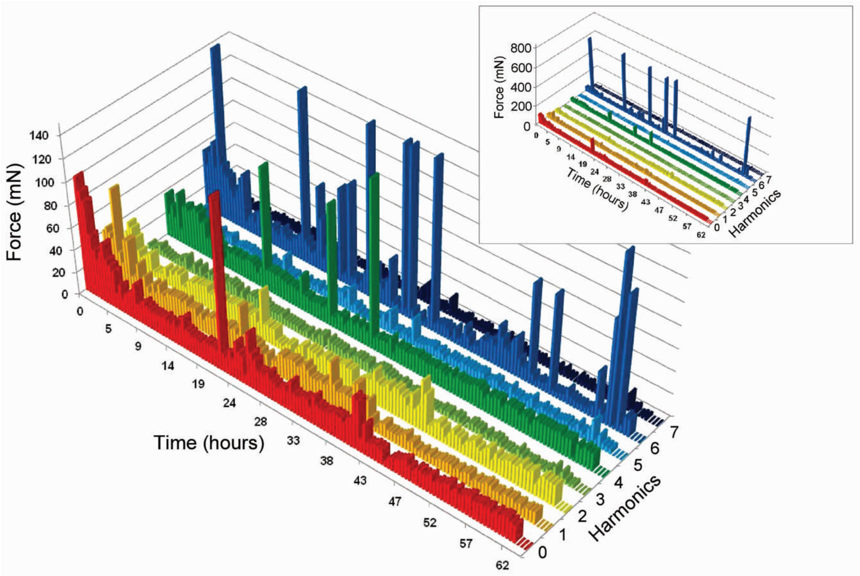

Figure 8. Microvibration reduction of the 1st 8 harmonics during 62 hours at 12.8W & 100K

The vibration reduction algorithm succeeds in significantly reducing the levels of the1st 8 harmonics. Although sporadic measurement errors on the harmonic number 6 of up to 800mN can be seen on the inset of Figure 8, which in certain cases has a knock-on effect on the other harmonics, whose levels are generally below 20mN. The initial convergence can be seen to be rather slow, requiring several hours, due to the limited processing power of the low power CDE. It should however be possible to improve this situation through optimization of the control loop parameters.

Cold Head Tests

Optimization of the CHA was performed in parallel with the CDE development, using a laboratory drive electronics. The CHA was driven by a standard MPTC compressor. Regenerator and inertance parameters were optimized. For inertance optimization, a buffer tool with an external inertance tube (see Figure 9) was used in place of the self-contained inertance/buffer assembly of Figure 3. The measured performance of the optimized MPTC at low input power is shown in Figure 10. Figure 11 gives the improvement in performance relative to the original MPTC design at 150K. Depending on the input power, the performance increase is between 8 and 23%.

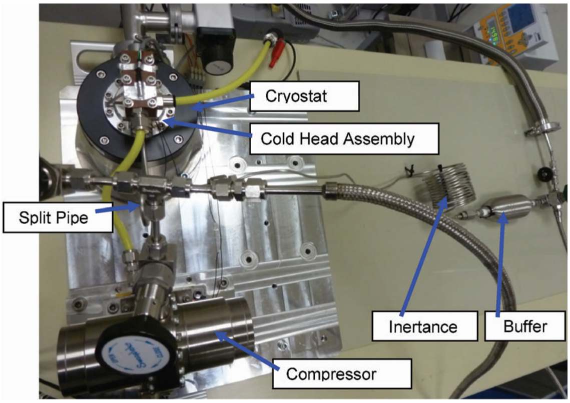

Figure 9. Temperature regulation mode @ 150K

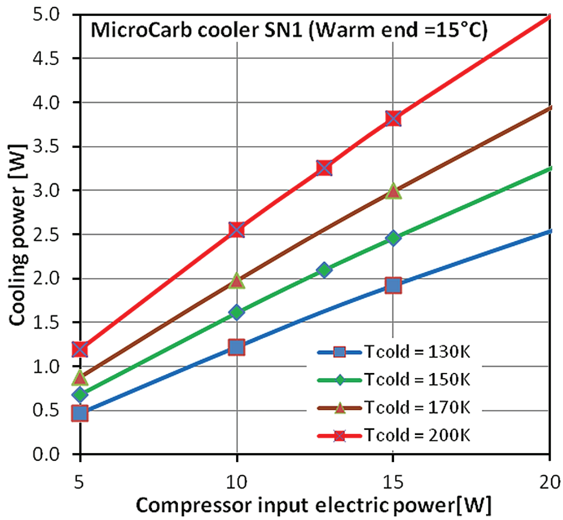

Figure 10. Cooling power with the warm end at 15°C

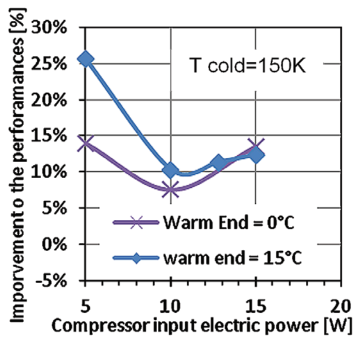

Figure 11. Improvement of cooling performance relative to original MPTC

Coupled tests of the EM cooler and CDE

Coupled tests of the EM cooler and EM CDE give the cooling performance results shown in Figure 12. Figure 13 gives the CDE efficiency deduced from these results. This efficiency is almost independent of the supply bus voltage in the range 20-40V.

Considering the various functions performed by the CDE including temperature control and active microvibration analysis and reduction, the power consumed by the CDE itself is significantly lower than most comparable systems for space applications.

Lifetime Testing

An 80K MPTC using the same compressor design and cold finger geometry has been undergoing lifetime testing since 2007 and has accumulated approximately 50 000 hours of continuous running time at 35W input power. No measurable deterioration in cooling performance has been observed during this time.

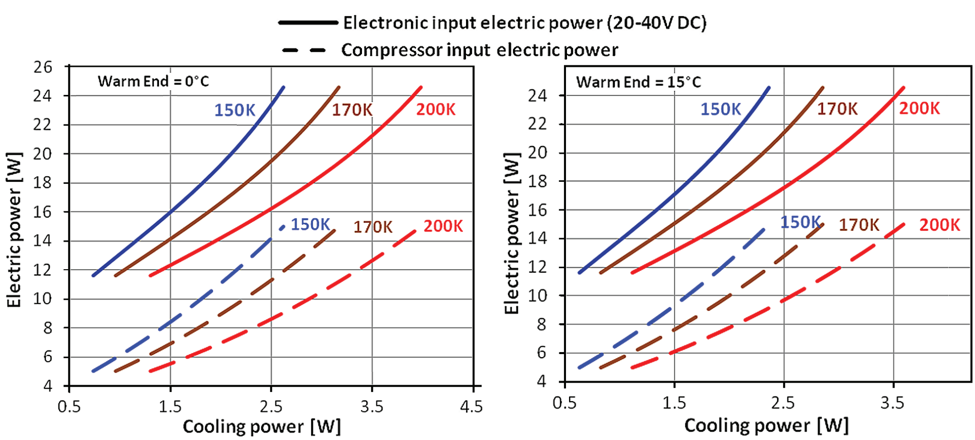

Figure 12. Performance of EM cooler including CDE

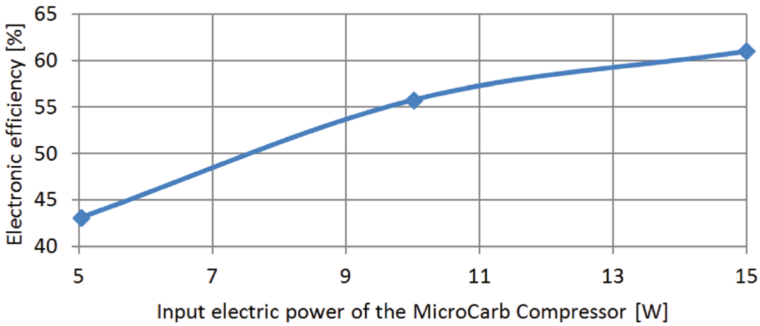

Figure 13. CDE efficiency for supply voltages in the range 20-40V

CONCLUSION

A small cryocooler for microsatellite missions has been manufactured and tested including a new cold head, new drive electronics, and an existing compressor design.

At 150K and 180K, we succeeded with the new cold head design to improve the performance by between 8% and 25% relative to the previous design which was optimized for lower temperatures and higher input powers.

A new compact, low mass and efficient CDE has been designed. With 5 W maximum dissipated power this CDE manages the temperature sensors, the cold interface temperature regulation, the compressor power regulation, and the micro vibration reduction controls.

The overall mass of the system including the drive electronics and harness is 5.3kg.

ACKNOWLEDGMENT

This work has been supported by the CNES (Centre National d'Etudes Spatiales) through contracts N°127683/00 and N°116055/00.

REFERENCES

1. Butterworth, J., Aigouy, G., Chassaing, C , Debray, B., Huguet, A., "Pulse tube coolers for Meteosat third generation", *Advances in Cryogenic Engineering*, AIP Publishing, Melville, New York, (2014), pp.520-524.

2 Trollier, T., et al., "Design of a Miniature Pulse Tube Cryocooler for space applications.", *Advances in Cryogenic Engineering*,, Transactions of the Cryogenic Engineering Conference-CEC., Vol. 710. No. 1. AIP Publishing, (2004), p. 1318.

3 Trollier, T., Tanchon, J., Buquet, J., and Ravex, A., "Status of Air Liquide Space Pulse Tube Cryocoolers," *Cryocoolers 15*, Interntional Cryocooler Conference, Boulder, CO (2009), pp. 115-123.

4. Chassaing, C., Butterworth, J., Aigouy, G., Daniel, C., Crespin, M., Duvivier, E., "150K - 200K miniature pulse tube cooler for micro satellites", *Advances in Cryogenic Engineering*, AIP Publishing, Melville, New York, (2014), pp. 525-532.