

Synergies between designed-for-space and tactical cryocooler developments

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ABSTRACT

In this paper, an overview is presented of the latest developments of space cryocoolers at Thales Cryogenics B.V. Planned future developments for the LPT6510 cooler are presented, and the synergies between Commercial-off-the-shelf (COTS) and space are reviewed, such as design principles from space coolers being applied to an upgraded variant of the COTS LPT9310, as well as design principles from COTS coolers being applied to the LPT6510 for improved manufacturability.

Thales performed a simulation and experimental study into the coupling of an off-the-shelf pulse tube to a designed-for-space, high-performance compressor, and a prediction is given regarding what performances could potentially be achieved with an optimized design.

INTRODUCTION

Cryocoolers for tactical and space applications are often considered to be completely different classes of coolers. However, the distinction between space mission specific cryocooler designs and tactical off-the-shelf cryocoolers has become less pronounced. Whereas the companies traditionally involved in designed-for-space cryogenics have adopted a dual-purpose design philosophy [1], cryocoolers originally designed for tactical applications have evolved to a point where these can be used in certain space applications with minimal adjustments [2].

Thales Cryogenics follows the latter path. Not only ‘full space’ products are being developed, but also commercially-off-the-shelf products are being used for space, mostly with either upgraded product and quality assurance or upgraded design features.

In this paper, we will first describe the synergy between both markets in terms of cooler requirements. Furthermore we will highlight a few example coolers.

SYNERGIES BETWEEN SPACE AND TACTICAL CRYOCOOLER REQUIREMENTS

In general terms, typical requirements for any cooler can be described in terms of lifetime, reliability, efficiency, robustness, and others. Any application would want to maximize any of these characteristics. However, there are some differences.

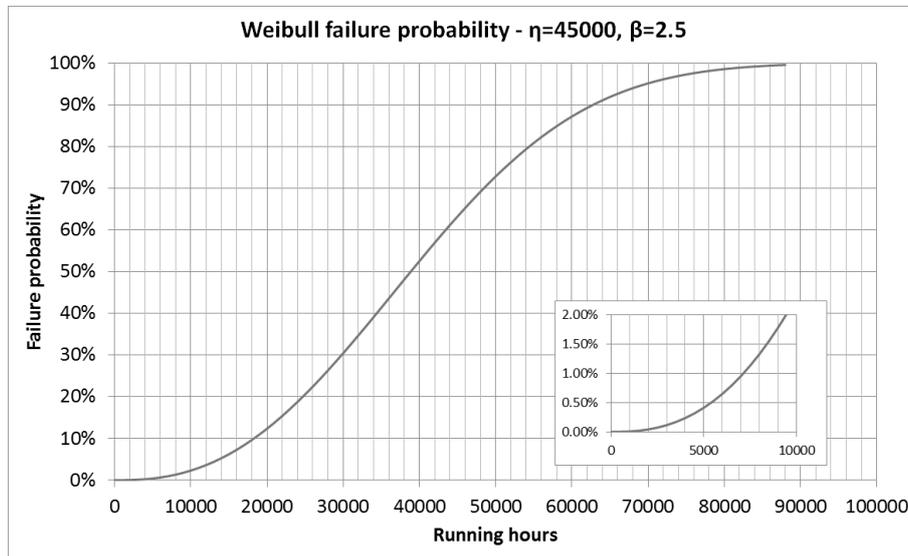


Figure 1: Weibull statistics of a high-reliability free-displacer Stirling cooler with flexure-bearing compressor.

Reliability

Reliability matters for any cryocooler application. However, there is a profound difference in the formulation of the reliability requirement. The reliability figure of merit for a tactical cryocooler is the MTTF, signifying the amount of running hours after which there is a 63% failure probability. Implicitly, this means that for tactical cryocoolers, delivered in volume, a certain amount of failures during operation are considered acceptable.

For a space application, the typical usage scenario requires multi-year operation with an extremely high survival probability, with reliability figures exceeding 99% required for the full mission lifetime.

In Figure 1, the Weibull-shaped failure probability for a typical high reliability tactical cryocooler is shown. It is immediately apparent from examining this curve that even when a failure probability of 1% over the mission life is accepted, a high reliability free-displacer Stirling cooler will not suffice for missions requiring more than 7000 hours of operation. While this type of reliability may be considered acceptable for certain Operationally Responsive Space (ORS) missions, for a mission where 1 year or more of 24/7 operation is required, a higher standard will be required.

Robustness

In both tactical and space applications, robustness versus mechanical loads is required. Whereas a tactical cryocooler can be expected to be subjected to mechanical loads more or less randomly during its entire operating life, for a space cryocooler the most severe loads are experienced during the short time interval of spacecraft launch, cooler non-operating.

Induced vibrations

Almost all space craft applications include some measure of sensitivity to vibrations generated by mechanical parts and systems. As the item to be cooled is typically an electro-optical detector of some kind, any kind of motion introduced by the mechanical cooler can adversely affect image quality.

For many tactical applications induced vibrations are not a problem as such. For many usage scenarios, the detector (and cryocooler) are hard-mounted to a heavy system, and the forces induced by the cryocooler on such a system will result in a negligible amount of motion of the detector. Sensitivity to induced vibrations in non-space applications manifests itself in different requirements:

- Acoustic noise (non-detectability)

- Line of sight stability in specific applications (small gimbal)
- Image blurring effects in high sensitivity applications, i.e. X-Ray microscopy
- Microphonic disturbances for certain high-sensitivity detectors, such as Germanium detectors used in gamma ray spectroscopy.

Power efficiency and power density

The trend towards small-size, low-mass high-efficiency cryocoolers is present in both tactical and space applications. In both, it is the system-level impact of design choices that needs to be examined. The optimum for a given scenario is not always apparent.

For example, in a typical hand-held tactical application, choosing a less efficient cooler which has a higher power density (higher maximum cooling power) can make sense in a usage scenario where the ability to perform a rapid cooldown can negate the necessity for 24/7 operation – thereby significantly reducing the cooler ON hours and reducing the required battery capacity for autonomous operation.

The argument for a rapid cooldown negating the necessity for 24/7 operation is only valid in applications where there is an element of uncertainty in when full imaging performance is required. In a space application the duty cycle of the detector will, for the most part, be predictable, negating the necessity for a rapid cooldown. Power efficiency and low mass will be favored instead, although the mass impact of a higher cryocooler efficiency should always be considered against the mass impact of a higher power supply requirement, such as larger solar panels.

In the following paragraphs we will compare cryocooler designs for space and tactical applications, with the above in mind, after which we will examine a few practical cases.

COMPRESSOR DESIGN

It has been proven time and again that the Oxford-style compressor design, with flexure-supported pistons aligned inside a tight tolerance cylinder, is capable of operating continuously for several years with a very low failure probability. Many design elements of a space-pedigree Oxford-style compressor have since found their way into commercial off-the-shelf tactical flexure bearing compressors. Potential failure modes for linear compressors (e.g. as summarized in [3]) are mitigated or eliminated regardless of the field of use. For instance, because of the use of moving magnet linear motors the failure mode of feedthrough leaks and contamination are eliminated. Breakage of springs is mitigated by using well-understood design rules and inspection criteria. More information on failure modes and how they are applicable can be found in reference [4].

So the design principles for compressors are very comparable for both space and COTS products. The question then remains of whether a modern off-the-shelf flexure bearing compressor shows the kind of reliability statistics that are required for a space mission. Based on the reliability data obtained from known applications [5] it can be concluded that this is indeed the case for the Thales LSF93xx compressor series, used in the (COTS) LPT9310 pulse-tube cooler. Other Thales LSF-series compressors in series production show similar reliability statistics. It is therefore concluded that an off-the-shelf flexure bearing compressor design can be leveraged for a high-reliability space cryocooler, provided that no significant changes are introduced that can potentially result in an increased sensitivity to the known failure mechanisms.

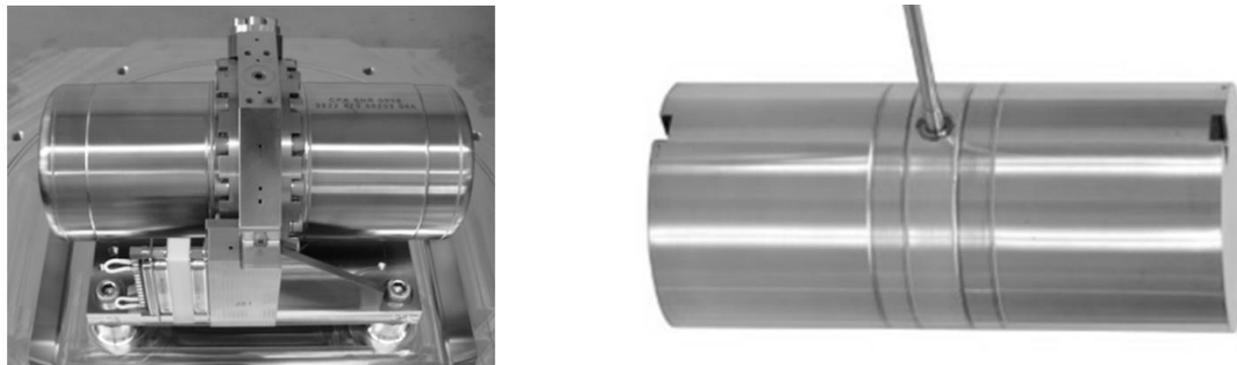


Figure 2: LPTC compressor (left) and LSF93xx compressor (right).

There obviously are differences between the two product ranges. For the comparison we consider the LSF93xx COTS flexure bearing compressor and the Thales LPTC compressor developed under ESA contract and used in various European space applications, such as the Air Liquide LPTC cooler for the Meteosat Third Generation (MTG) programme as well as the 30-50K dual stage cooler developed under ESA contract [6]. Both compressors are shown in Figure 2. The main differences are in the materials use and the mounting method of the motors. The LPTC uses an aluminium centre part to which the motor halves made of Ti6Al4V are bolted, whereas the LSF93xx use a hermetically sealed, all-welded stainless steel concept. The former has the advantage of low mass, higher strength, and adjustability of the motors. The latter has the advantage of not needing C-seals for the critical helium tightness and the intrinsic alignment because of the single cylinder.

COOLERS DEVELOPMENTS

COTS-Space Stirling versus designed-for-space pulse-tube coolers

One example where the synergy between COTS and Space products is clearly visible is the Thales LSF9199/30 linear Stirling cooler, developed originally for infrared detector manufacturer Sofradir for non-European space customers. It is compared to the LPT6510, developed in collaboration with Absolute System. The two coolers are similarly-sized and were designed for a comparable range of cryogenic performance requirements, but were designed from a different paradigm. For the purpose of this discussion we will focus on the differences in cold head design.



Figure 3: LSF9199/30 (left) and LPT6510 breadboard demonstrator (right).

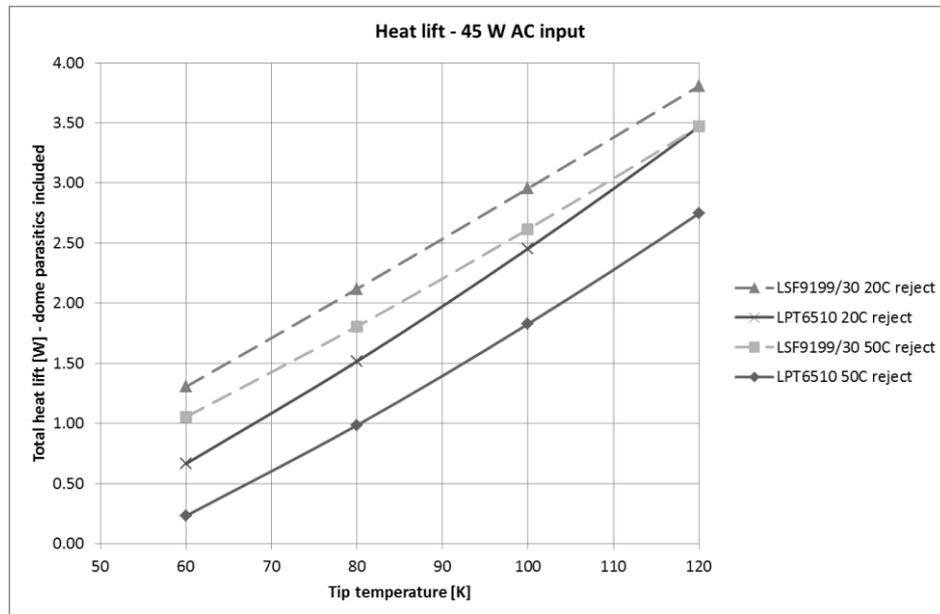


Figure 4: Heat lift - LSF9199/30 vs LPT6510.

The LSF9199/30 was designed as a cost-effective option for high-efficiency space cooler requirements [7]. As it has a pneumatically-driven free displacer, the efficiency of the cryocooler is high without the need for expensive, high-grade material combinations. Furthermore, the industry-standard SADA-compatible displacer design allows infrared detector manufacturers to adopt a similar COTS-to-space approach for the detector-dewar assembly.

The LPT6510, on the other hand, is designed from the ground up as a space cryocooler using high-end materials and processes, based on the high-efficiency MPTC compressor developed under ESA funding, and the Absolut System SSC80 pulse-tube cold finger, which is a performance-optimized pulse-tube design [8].

As can be seen in Figure 4, the LSF9199/30 is for the most part the more efficient cryocooler, which is typical when comparing a Stirling cooler to a pulse-tube cooler. However, the fact that the LPT6510 makes use of high-end materials and includes a more efficient compressor design closes part of the performance gap.

The advantage of a designed-for-space pulse-tube cooler becomes apparent if one examined the reliability; or the probability of reaching a long mission life with a very low failure probability.

For the LPT6510, the question of reliability is not difficult to answer. Both for the flexure-bearing compressor concept and the pulse-tube cold finger the potential failure mechanisms are well-understood and large amounts of statistical data are available.

For the LSF9199/30 cooler, less directly-applicable data is available. The reliability characteristics of a linear-moving flexure-supported mass are well-understood and the design should enable reliability statistics similar to those of a pulse-tube cooler, but the fact remains that adding a moving displacer to the cooler adds a failure mode (Expander blow-by, as per [3]).

If design, qualification, and in-site inspections and tests during production are of a sufficiently high standard, a cooler with a flexure-bearing displacer can still be expected to reach the extremely low failure probability required. The flexure-bearing free displacer concept was placed in life time testing during the CryoSystem project, with 4 units operating within specification after more than 10 years of continuous operation each in the Thales Cryogenics life time lab.

Summarizing the above, it can be concluded that a cost-effective high-efficiency solution is possible by making use of the building blocks of a tactical cryocooler, such as what was done with the LSF9199/30, provided the user is willing to make compromises when it comes to exported vibrations and the proven reliability statistics of the solution. If a no-compromise

solution is required, a designed-for-space pulse-tube cooler such as the LPT6510 has significant advantages.

LPT6510 pulse-tube cooler development

The LPT6510 cryocooler was previously developed up to TRL 4. Thales and Absolut System are currently partnering to perform a self-funded development, with a target to reach TRL 7 by the end of Q2 2019. The targeted usage range of this cooler is to provide lift at temperatures from 60 K to 150 K.

Detailed design of the cooler is being finalized. Trade-offs have been performed in order to optimize performance and reliability, and to minimize complexity, mass, and volume. Compliance with ECSS standards is targeted.

In these trade-offs, COTS design principles are being considered. The all-welded compressor design limits the need for c-seals. A single interface for the entire cooler (mechanical and thermal) is obtained by including a central heat sink bracket. A CAD rendering of the updated design is shown in Figure 5.

The processes used for the LPT6510 compressor are used and qualified for flight hardware in the various LPTC programs. This includes welding steps (electron-beam and laser), bonding, wiring connections etcetera. At the same time, the LPT6510 pulse-tube cold finger is based on the heritage of the Absolut System SSC80, with all production processes based on those used for flight-qualified pulse-tubes in the past.

It can be concluded that in the LPT6510 cooler, the design and manufacturing principles of the space-coolers are combined with those of COTS products, to realize a compact and efficient solution for future space missions with 10 years or longer mission lifetime.

Optimization of a COTS pulse tube for integration with a space compressor

In a previous project [2], where the expected mission life did not require a ‘full space’ solution, a cooler based on the COTS LPT9310 has been used. In this mission, the LPT9310 was updated slightly to improve the efficiency by changing to Ti6Al4V. At the same time, additional effort was put into additional process qualifications.

As stated before, full-space products are usually further optimized for efficiency than COTS products. One difference between the LPT9310 cooler and the LPTC space cooler is the efficiency of the compressor.

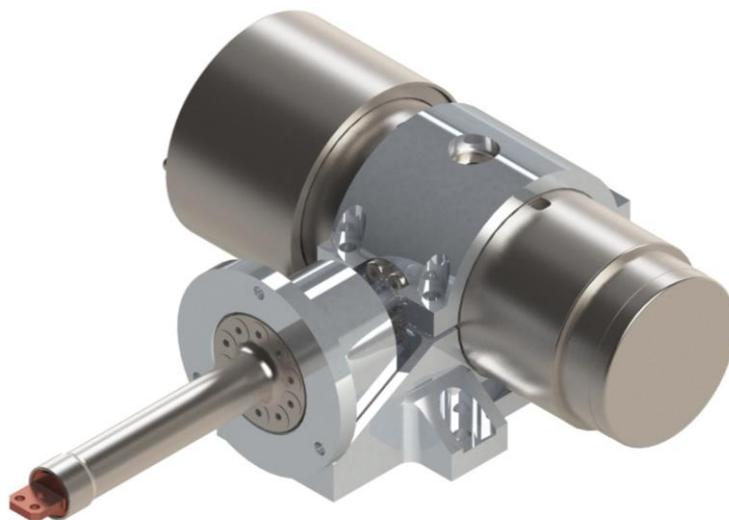


Figure 5: CAD Render of the updated LPT6510 design.

It was investigated what the potential performance would be of a combination of the LPTC space compressor and the performance-optimized LPT9310 pulse-tube cold finger.

Some design optimization had to be carried out, as both coolers operate at different driving frequencies. In order to get a correct integration of compressor and cold finger, the dynamics need to be optimized for two aspects: Resonance in the compressor to maximize compressor efficiency and correct phase shifting in the pulse tube to maximize the cold-finger efficiency. Both depend on drive frequency and fill pressure.

The optimization was carried out in two stages. First the expected performance was simulated using the SAGE software [9]. SAGE allows the prediction of performance. The SAGE model was expanded to include the losses in the compressor, mainly resistive losses in the coils, and eddy current losses and dynamic losses in the stators and other structural parts. This then adds the simulation of compressor efficiency for a given set of input parameters.

To maximize the use of existing components and to limit the amount of variables to be optimized, all the geometry was kept the same. The only variables subject to optimization were the length and diameter of the inertance tube and the drive frequency. No additional optimizations on the pulse-tube cold head were done. So the regenerator matrix was kept the same, while this would be a suitable optimization in a later stage if the cooler is optimized for a specific temperature range. The LPT9310 cooler is optimized for a tip temperature of 80 K.

The system was optimized for maximum efficiency. This is the product of the thermodynamic efficiency of the cold head and the electrical efficiency of the compressor.

In a second part, the performance was measured on a breadboard model consisting of an LPTC compressor and an LPT9310 cold head. The latter was adapted to allow the integration of different inertance tubes. In the standard LPT9310 pulse tube design as licensed from CEA, the inertance tube is placed inside the buffer volume. This buffer volume was replaced by a separate buffer and replaceable inertance tube. On both sides of the inertance tube adaptor pieces were placed to ensure a smooth flow transition and the connection of pressure sensors. A photograph of the test setup is shown in Figure 6.

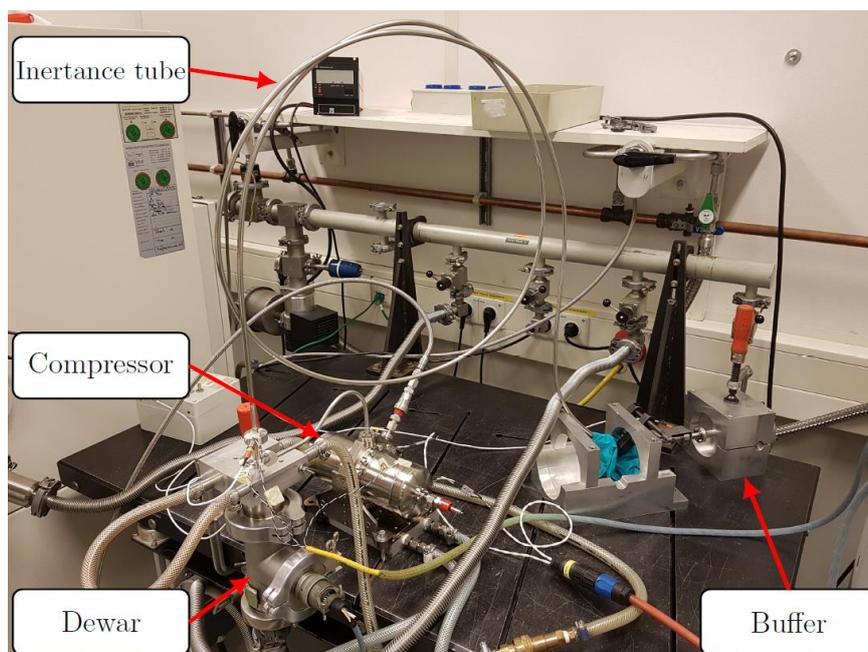


Figure 6: Photograph of test setup of the LPTC compressor with LPT9310 cold head.

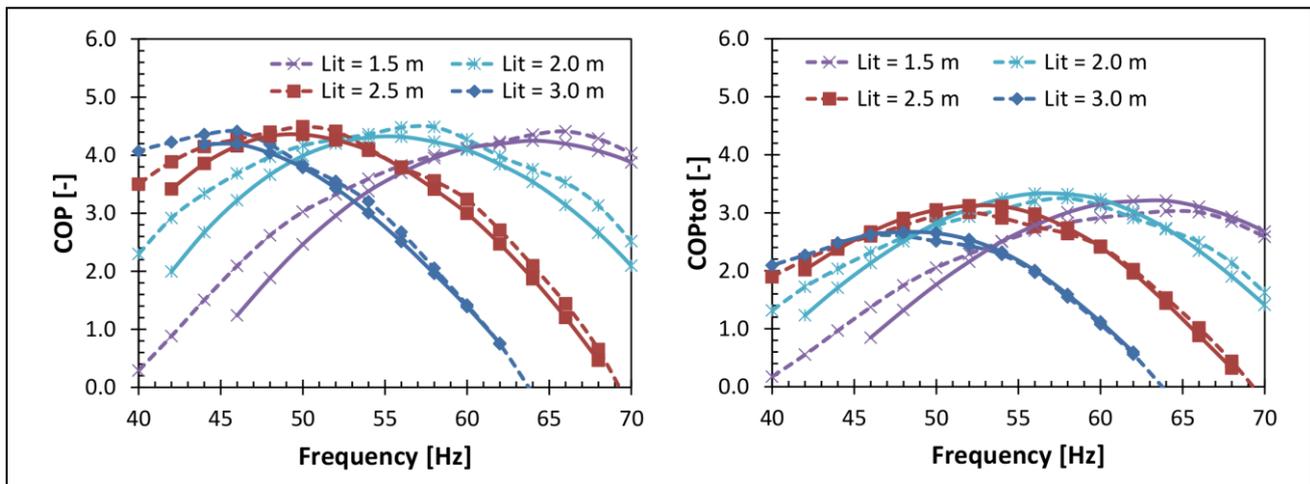


Figure 7: Simulation results (dashed lines) and experimental results (solid lines) for one diameter and different lengths of the intertance tube. Left graph shows the thermodynamic efficiency, the right graph the overall system efficiency.

The experiments and simulations were carried out as a mapping. The performance of the system was optimized for maximum efficiency. In order to have comparable results for all configurations, the electrical input power was fixed at 145 W. To achieve this, the piston amplitude was adapted for each simulation set.

Not all simulation results will be presented here. However, for one diameter of the intertance tube the simulation results and experimental results are shown in Figure 7. Here, the thermodynamic efficiency $COP = \text{Cooling Power}/\text{Mechanical Power}$ and $COP_{\text{tot}} = \text{Cooling Power}/\text{Electrical input power}$ are shown. The total efficiency can be measured directly. The mechanical efficiency is derived from other measurements. The ratio between the total efficiency COP_{tot} and the mechanical efficiency COP is then equal to the electrical compressor efficiency COP_{el} .

From the thermodynamic efficiency graph, it can be seen that for each length of intertance tube, there is an optimum drive frequency. For each intertance tube, a near optimum phase can be reached at the right frequency. Furthermore, it can be seen that the maximum efficiency for each intertance tube length is comparable. This means that the cold head can be used over a wide range of frequencies without too much impact on efficiency, by using the correct intertance tube.

If the compressor efficiency is included (right-hand side in Figure 7), there is a clear optimum in overall system efficiency. For this intertance tube, the optimum efficiency is reached at an intertance tube length of 2.0 m and a drive frequency of 57 Hz. At this combination of length and frequency the optimum phase shift in the intertance tube is combined with maximum

These calculations have been carried out for different intertance tube diameters. For each diameter, an optimum length and drive frequency are determined.

The overall results are shown in Table 1. In this table, three variants are summarized: the results for the standard LTP9310 cooler, consisting of the cold head with LSF93xx compressor. The second configuration shows the results when the LSF93xx compressor is directly replaced with the LPTC compressor, and the third configuration is the LPTC compressor with LPT9310 cold head with optimized intertance tube and drive frequency.

It can be seen that when compressors are directly swapped, the overall system efficiency decreases dramatically.

It can be seen that the optimum frequency for the first two configurations are comparable, because the same intertance tube is used. However, because the compressor and pulse-tube are not matched, the overall efficiency decreases. In case the intertance tube is optimized, the total efficiency is increased to 3.5%. This increase in efficiency of nearly 20% is mainly caused by the significantly higher compressor efficiency of the LPTC compressor at resonance.

Table 1: Overall results for three optimized geometries.

	Freq. [Hz]	COP _{el}	COP	COP _{total}
LPT9310 standard	46	61	4.9	3.0
LPTC/LPT9310 standard	48	54	4.6	2.5
LPTC Optimized	58	79	4.4	3.5

As stated before, the electrical conversion efficiency of the compressor is a rough estimation. For the combination of the LPTC compressor with standard LPT9310 pulse tube, this most likely caused a large error. The overestimation of the electrical efficiency leads to an underestimation of the mechanical efficiency.

On cooler level it means that the cooling power will increase from 5 W at 80 K for the standard LPT9310 pulse tube cooler to 5.9 W at 80 K for the optimized version. It should be noted furthermore that the tested configuration is the stock LPT9310 cold head, optimized for 80 K tip temperature. In case additional performance is needed, as was the case in the Ecostress project [2], further options are available or additional optimizations such as the regenerator matrix or a stepped diameter inertance could increase the cooling power or reduce the attainable tip temperatures.

CONCLUSIONS

Several options are available for space coolers built from off-the-shelf building blocks. However, these options typically require a compromise on one or more parameters, such as mass, induced vibration, or efficiency. The various examples have been presented such as the LSF9199/30 Stirling cooler which has excellent intrinsic efficiency, but requires additional care in controlling exported vibrations.

The reverse approach has also been discussed, with design principles from off-the-shelf coolers being used to reduce cost, manufacturing complexity, and integration complexity, without requiring the end user to compromise on performance characteristics. This paradigm is being implemented in the LPT6510 pulse-tube cooler, with a targeted cooling power of 3W at 100K. Planned TRL level of 7 is to be reached in Q2 2019.

This is further investigated in a concept study where an off-the-shelf LPT9310 pulse-tube cooler is coupled to a space-qualified LPTC compressor. After optimization of the inertance tube to dynamically couple the compressor and cold head, a performance improvement of nearly 20% is reached.

Options are currently available at Thales Cryogenics for a variety of requirement sets, and feedback from end users concerning the trade-offs presented is welcomed.

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