High-Availability Cooler Developments at Thales Cryogenics

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ABSTRACT

Thales Cryogenics has previously presented its developments in the field of High-Availability (HA) coolers. In this paper, we present our recent advances in this development program. The initial development was aimed at a HA Stirling cooler for HTS filter applications. An update of lifetime numbers of those Stirling coolers, now running continuously for nearly 5 years without degradation, will be given as an indication of the current and expected availability of the technology.

Recent advances include the development of two new Stirling coolers. Thet development status and performance measurements of these coolers will be presented; they are designed to be integrated with industry-standard ¼" and ½" (SADA2) dewars. This allows the use of HA Stirling coolers in a wide variety of infrared applications. In addition, the use of pulse-tube coolers for infrared sensing applications will be discussed, as the pulse-tube cooler remains the technology of choice for applications requiring a vanishingly small failure probability.

INTRODUCTION

Thales Cryogenics produces a large range of cryogenic coolers for various applications. These coolers are based on the Stirling or the pulse-tube principle. Different applications impose different requirements on the coolers that are used. In this paper, we will present improvements that have been implemented on linear Stirling coolers to make them better suitable for the intended use. In previous papers [1-3], initial developments in this field were presented. In this paper, we give an update on the status of those developments, and furthermore present new developments.

The term 'Availability' is used as a figure of merit to describe the reliability of a system, particularly for applications that require 24/7 operation over long periods of time. Traditionally, reliability is expressed by the Mean Time To Failure (MTTF) of a system [4,5]. This is determined statistically, for large population of systems. Typically a Weibull distribution is used. The MTTF is defined as the amount of time after which 63 % of a population will have failed.

For systems requiring 24/7 operation without interruption or disturbance, using 'availability' as a figure of merit is more appropriate. Availability represents the probability that a system will function according to specification for a set amount of time. It is the inverse of the failure rate.

Flexure bearing compressors are known for their extremely long lifetime .When combined with pulse-tube cold fingers, the lifetime is virtually infinite [6]. Stirling coolers can also benefit from the high reliability of flexure bearing compressors.

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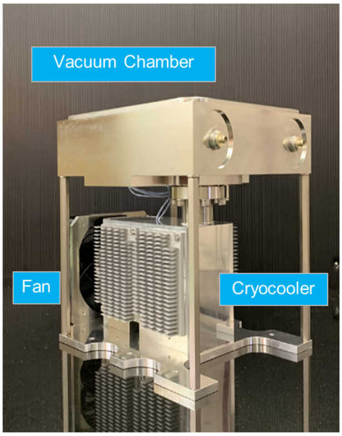

Figure 1. The the LSF9589 cooler (left) is the first cooler in our high-availability Stirling cooler family. The right shows one of the possible applications: a cryogenically cooled superconducting RF filter modules (pictures courtesy of Toshiba Hokuto Electronics). The module on the right is 274 mm high, 242 mm deep, and 207 mm wide [4,5].

The main difference between Stirling coolers and Pulse-tube coolers in terms of reliability is a fundamental one. Even though Stirling coolers have been improved to achieve high availabilities, the main failure mode remains a wear-related one, increasing blowby due to wear of the primary displacer seal. Pulse-tube coolers do not show that wear-related failure mode and will therefore always have a better reliability and availability compared to Stirling coolers. This will be further discussed in the final section of this paper.

First, we present the ongoing developments in our family of high-availability Stirling coolers including our newest developments, particularly the IDCA versions (¼ " and ½ " versions). These developments are aimed at improving the performance of the coolers in their intended applications. One such application is the cooling of high-temperature superconducting (HTS) filter electronics. Such an application requires continuous operation (24/7) over a long period of time. In Figure 1 an example is shown where a Thales LSF9589 cryocooler is used to cool a superconducting filter and a low-noise amplifier (LNA). This cooler and application were both previously presented [1,7,8]. We will summarize the current status of lifetime endurance testing, both in lab testing as well as in the field.

LSF95XX HIGH-AVAILABILILTY STIRLING COOLERS

LSF9589 lifetime status

Our first HA Stirling cooler, the LSF9589 cooler, is shown above in Figure 1. This is a so-called slip-on version of a Stirling cooler with updated low-force bearing design. This model is now being series produced, and the design is considered mature.

Apart from the field-proven reliability, a lifetime lab test is being conducted since the qualification of these coolers. In total, four coolers have been placed in a 24/7 lifetime test. The coolers are being subjected to regular performance measurement to determine the performance evaluation as a function of time. In Figure 2, the performance measurements for all four coolers are shown.

The expected main wear-related failure mode for any Stirling cooler is increasing blowby due to main seal wear [5]. In a lifetime performance trend as shown in Figure 2, this would be visible as a slowly decreasing cooling power over time. When the performance drops below the specified cooling power, the cooler is considered End-of-Life (depending on the actual cooling load from the application). In Figure 2, such a decrease is not visible yet. This could mean that either the failure mode is not present anymore, or it is not yet visible on the current time scale.

Each of the four coolers is approaching 5 years of continuous operation. In total, more than 165,000 running hours have passed. No performance degradation is visible on this time scale.

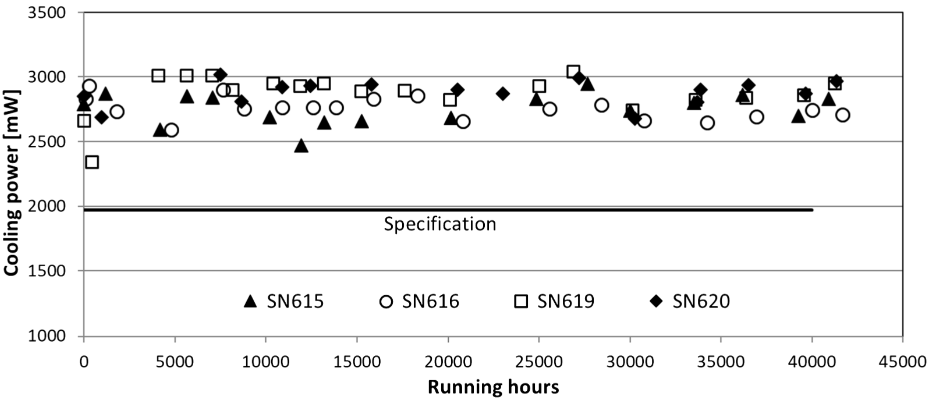

Figure 2. LSF9589 lifetime test results

As stated, the LSF9589 is a so-called slip-on type cooler. As such, sealing the vacuum around the cold finger is implemented using a CF-type flange with a metal seal. While this type of sealing is considered good for holding a vacuum, it is generally considered as a best-practice for long-life infrared dewar applications to have a welded dewar which is baked, pumped, gettered and pinched shut to achieve a long-lasting permanent vacuum. This is what is typically done in an IDCA-type cryocooler design.

As the LSF9589 cooler has a Stirling displacer diameter identical to the displacer used for SADA-II dewar compatible half-inch cryocoolers, Thales has tested an IDCA version of this design which is described in the next section.

LSF9599 High Availability demonstrator

Based on the displacer of the HA version LSF9589, three demonstrator coolers were built to ensure the performance remained intact when bringing the concept to an IDCA-type cryocooler. In this demonstrator, we demonstrated the cryogenic performance as well as the main bearing, alignment, and integration concepts.

The results of these demonstrators were compared to the standard LSF9599 cooler, and curves can be seen in Figure 3. As can be seen, the three demonstrator coolers performed better than the average performance data for a standard LSF9599.

No specific effort has yet been made to optimize performance. Based on the observed differences in performance between the three units, the window of operating conditions (mainly frequency and dynamics) were fine tuned to minimize performance variation from unit to unit. This, however, needs to be verified in subsequent detailed development steps.

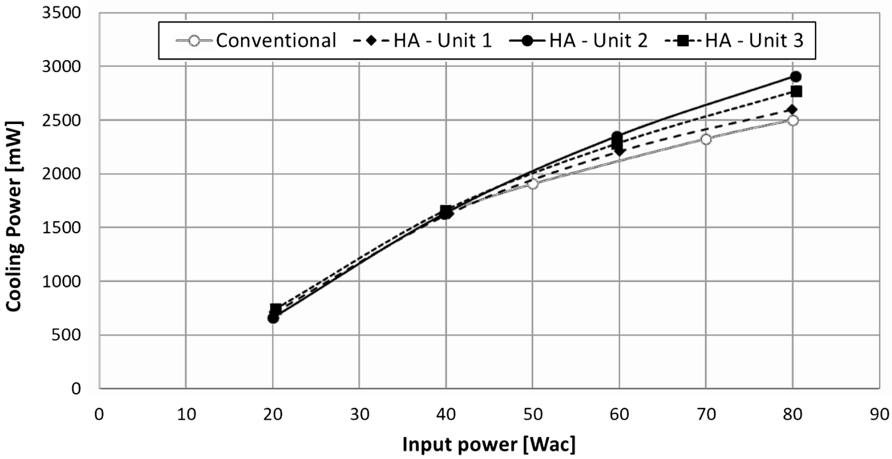

Figure 3. Performance of the first 3 LSF9599 demonstrator units.

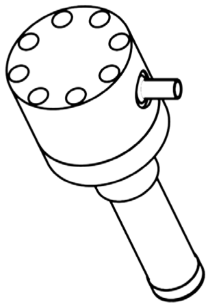

Figure 4. CAD outline of the LSF9599-HA cold finger.

It was thus found that a high-availability version of the 1/2 ", SADA2 compatible cooler, is expected to have at least identical performance as the conventional version. In a next step, a full qualification and industrialization should take place. As a first step, the two best performing demonstrator units will be placed on lifetime testing.

Interface dimensions of the LSF9599-HA are comparable to the standard version and compatible with SADAII IDCA dewars. A CAD outline of the cold finger with protection cap is shown in Figure 4.

HIGH-AVAILABILITY COOLER ROADMAP AND ONGOING DEVELOPMENTS

Thales intends to eventually develop high-availability versions of all its Stirling cold fingers. An outline roadmap is given below in Table 1.

LSF9x97 High-availability ¼" IDCA coolers

The findings and design rules found in the development of the larger 13 mm and 20 mm cold fingers are currently being implemented in the ¼" IDCA Stirling coolers, the LSF9597 and the LSF9997. Both share the same cold finger, with different size compressors. A photograph of the latter is shown in Figure 5.

These coolers are both compatible with the Thales-standard ¼" IDCA interface, used in both linear and rotary cryocooler models (LSF9x97, UPxx97, RM2, RM4) and as such a high-availability version

Table 1. Roadmap of the High-Availability Stirling cooler developments.

Cold finger interface	Cooler type	Planning
20 mm slip-on	LSF9340	Available today [1]
20 mm IDCA	LSF9350	Development to be initiated Can be rapidly developed based on LSF9340 in case of operational need. Optimization options for higher power density or lower tip temperatures available.
13 mm slip-on	LSF9589	Available today [2]
13 mm IDCA (SADA-2 compatible)	LSF9599	Demonstrators available, performance evaluated. Initial production can be started
9 mm IDCA	LSF9548	Development to be initiated
8 mm IDCA	LSF9508	Development to be initiated
¼" IDCA	LSF9597 LSF9997	Development in progress – life time test planned to start Q3 2022, available on market Q4 2022

Figure 5. LSF9997 1/4" IDCA cooler with flexure bearing compressor.

can be used as a drop-in replacement without requiring any dewar development. It was thus very important in the development to ensure that the warm end of the new ¼" cold fingers remains within the existing space envelope, to ensure a true form-fit solution.

The current status of the development is that the main design choices, particularly the low-side force displacer suspension, have been finished and validated. The same approach has been used as presented in [2], then implemented for the 13 mm displacer. The updated suspension was measured for side forces using the spring force reaction measurement bench. It was confirmed that the remaining side forces are at least one order of magnitude lower than the gravitational load on the bearing. Subsequent performance testing is foreseen in summer 2022.

The target MTTF of the upgraded ¼" cold finger is over 100000 hours, to be validated by life time testing. As the remaining force acting on the displacer bearing will be due to gravity, the life time in zero-g applications is expected to be even larger. As the total cooler weight is only slightly over 1 kg, this makes this cooler an attractive option for both 24/7 observation systems and cost-effective, high-reliability space applications (e.g. cube sats).

PULSE-TUBE COOLERS FOR INFRARED DEWARS

Cooler availability – Stirling versus Pulse-tube

While the life time results of the low-force bearing design are extremely promising, the fundamental advantage of pulse-tube technology remains – the absence of any wear mechanism will always prove superior to a reduction of wear. With the currently available lifetime test data for LSF9589 and LSF9340/60 coolers, the expected availability of 98 % after 5 years of operation appears to be proven. A similar estimate can be made for our pulse-tube coolers based on the installed base and known use profile.

The following numbers are known:

- Delivered since 2006: ~3000 coolers
- Accumulated running hours in the application: >100.000.000
- Number of coolers operating > 5 year: ~1500

As stated, the failure mechanism for Stirling and pulse-tube coolers are different. For Stirling coolers, it is wear-related, which means that the chance of wear-out increases over time. In a Weibull reliability analysis, this means that the 'shape factor' beta is larger than one. There thus will be an amount of running hours after which a large part of the population will have failed.

For pulse-tube coolers, there is no wear-out mechanism known, other than the slow leak of working gas which will only have an effect after tens of years. Therefore, it is assumed that the failure probability of a cooler is completely random, and will not increase over time. This assumption is strengthened by the extremely low number of failures known for these coolers.

With the numbers presented above, and the assumption that the Weibull shape factor equals 1, an expected availability after 5 years is 99.9%, and 99.7% for 10 years.

However, the pulse-tube design built to date is intrinsically a slip-on design. This means that in a high-availability infrared sensing application, additional care is needed to ensure dewar life time does not become limiting for system availability. Slip-on designs typically rely on dismountable vacuum seals, such as the CF flange used in the HA LSF9589 Stirling cooler (Figure1). For permanent-vacuum dewars, an all-welded vacuum system is preferred to ensure vacuum reliability. This design change on the cold finger also poses some system-level challenges.

Using pulse-tubes for infrared applications

For an effective pulse-tube IDCA design, a number of design details need to be changed compared to the classic pulse-tube design. Work is currently underway at Thales Cryogenics in cooperation with select customers to define a permanent-vacuum IDCA based on the Thales LPT9510 pulse-tube.

Design changes include:

- A low-CTE cold tip enabling direct connection of the infrared sensor
- Dismountable working gas connections and dismountable buffer assembly
- Correct weld geometries and tolerances for optical dewar assembly

The first demonstration hardware is expected to be available for select end-users Q4 2022. Currently the process optimizations and qualifications have been completed, parts for performance evaluation are being procured. A CAD rendering of the proposed solution is shown in Figure 6.

While the pulse-tube cryocooler has been the go-to cryocooler technology for spaceborne infrared sensing applications, the typical spaceborne cryostat architecture makes use of a cold plate that is connected to the cryocooler by means of thermal links.

The motivation for this architecture is derived from aspects such as:

- Mechanical decoupling of detector from cryocooler,
- Enabling the use of two cryocoolers connected to one cold plate (redundancy).

Cryostat architectures like this tend to be much larger than their IDCA counterparts. Their size and the fact that vacuum pumping is required, makes electro-optical testing on ground complex. An IDCA-type infrared detector for space applications can be an attractive solution, as a simple atmospheric-pressure optical test bench can be used for many tests. Redundancy in cryocoolers will be more complex, but there will be significant advantages in the possibilities for on-ground testing and a reduction in instrument size, complexity, weight, and (launch) costs.

The need for redundancy depends strongly on the expected cooler reliability. Redundancy should not be needed for many applications, based on the field-proven availability numbers for Thales pulse-tube coolers.

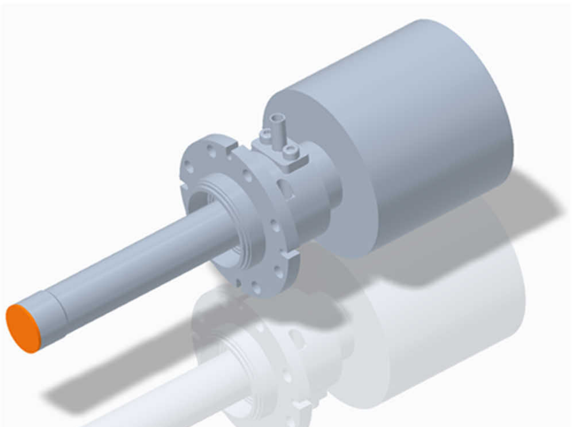

Figure 6. CAD render of the dismountable LPT9510 pulse-tube cold finger for IDCA applications. The cold tip has been modified (low CTE material), a weld flange is added to the mounting flange and dismountable gas and buffer connections are present.

CONCLUSION

In this paper, an update was given on the ongoing developments in the field of High-Availability Stirling coolers and the use of pulse-tube coolers in infrared sensor applications.

The mature LSF9589 cooler, the first in the HA cooler family, has proven its reliability in lifetime testing in both lab and field. Work is ongoing to apply the high-availability Stirling concept to various IDCA-type coolers. A first demonstrator cooler was designed using a SADA-2 compatible high availability cold finger. Three units were tested for performance. Next up will be a cooler based on the Thales standard ¼" size displacer.

The lifetime analysis and test results show that indeed significant improvements in MTTF numbers for Stirling coolers can be achieved. The resulting availability of these coolers is expected to be 98 % or higher after 5 years of use. This means that for some applications, expected reliability of these kind of Stirling approaches that of pulse tubes. However, due to the absence of wear related failure modes, pulse-tube coolers still have significantly higher availability than Stirling coolers, and will therefore remain the preferred cooler type for applications in which an extremely low failure probability is required. Work is ongoing to define a pulse-tube cooler for IDCA-type integration that will combine the reliability of the pulse-tube cooler with the industry-available sensor integration technologies.

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