High-Availability Stirling Coolers

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ABSTRACT

Thales Cryogenics has recently introduced a range of coolers for applications requiring a high availability. The availability is a figure of merit describing the reliability of a cooler in applications with long-term and continuous (24/7) or near-continuous operation. A high availability is synonymous with an extremely low failure probability. A well-known solution for a high-availability application is a pulse-tube cooler, such as those produced by Thales Cryogenics, which have an intrinsically high availability due to the absence of moving parts in the cold head. However, other aspects such as power density, power efficiency, or cooldown time prohibit the use of pulse-tubes in some applications. High-availability Stirling coolers can be considered in these cases.

A range of Stirling coolers is available for such applications. In this paper, we will present these coolers and some of the improvements that have taken place. The improvements to the coolers, in the 100 W to 200 W input power range, are not only intended to increase the availability – or reliability – of the coolers, but are also aimed at improving the performance, by either increasing the efficiency or extending the operating window.

In addition to performance and reliability improvements, the integration aspects of these cooler types will be presented, and system-level considerations discussed.

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 were done on linear Stirling coolers to make them more suitable for the intended use. In a previous conference [1], initial developments in this field were presented. In this paper, we will give an update on the status of those developments, and furthermore present new developments. In particular, a high-power, high-availability Stirling cooler will be presented.

The term High-Availability is used as a description of the reliability of a cooler. Availability is related to the reliability of the cooler. Reliability analysis is often based on Weibull statistics [1]. Here the mean time to failure (MTTF) is used as a figure of merit for the life time and reliability of the cooler. MTTF is 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.

Cryocoolers 21, edited by R.G. Ross, Jr., J.R. Raab and S.D. Miller

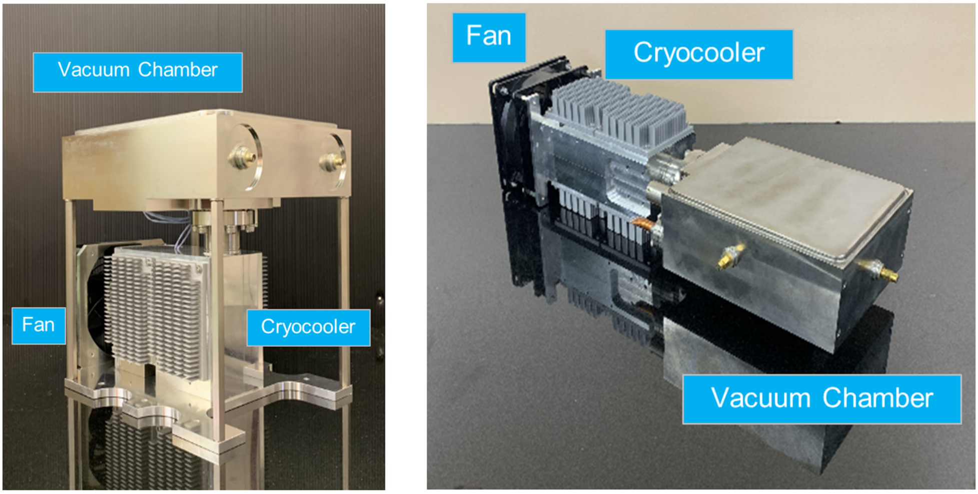

Figure 1. Two cryogenically cooled superconducting RF filter modules (pictures courtesy of Toshiba Hokuto Electronics). The module on the left is 274 mm high, 242 mm deep, and 207 mm wide [4,5].

Flexure bearing compressors are known for their extremely long lifetime [2]. 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. If a cooler type is to be chosen for a particular application, a trade-off has to be made. Pulse-tubes have near infinite life and extremely low induced vibrations, whereas the advantage of the Stirling cooler is a higher efficiency and a higher power density. If the advantages of the Stirling coolers can be combined with the lifetime expectations of pulse-tube coolers, the resulting product would be a high-power, high-availability cooler.

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 high-availabilities, the main failure mode remains a wear-related one. 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.

In this paper, we present recent developments on two of our Stirling cooler families. 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 low-noise amplifier (LNA). These systems can be used in commercial applications such as mobile communications as well as scientific astronomy applications. The advantage of the HTS technology used in this application is not just the well-defined, sharp filter cutoff typical for HTS designs, but also the superior noise performance at relatively high cryogenic temperatures, typically 77 K [4,5]. For large-scale astronomy projects such as the Square Kilometer Array (SKA), this could give a significant benefit in power consumption compared to traditional LNA systems requiring multistage 10 K coolers, combined with a maintenance free operation over long periods of time. Stirling coolers are preferred for these applications because of the advantages in power consumption and power density.

The improvements that were done on the cooler have been presented previously [1]. We will summarize these improvements and update the current status of lifetime endurance testing, both in lab testing as well as in the field.

A new development that will be presented is the transfer of the high-availability design of the 13mm cooler to the 20mm Stirling cooler, combined with an updated tuning of the cold finger to increase the available cooling power. The resulting cooler is a high-power Stirling cooler, suitable for 24/7 use in applications such as the boil-off recondensation of liquid nitrogen systems.

LSF9589 HIGH-AVAILABILITY STIRLING COOLER

From the well-known failure mechanisms for Stirling-type cryocoolers, e.g. as presented by Ross et al. [3], the dominant wear mechanism can be found in the cold finger. This is especially the case if the cooler is equipped with a flexure-bearing compressor, as a flexure-bearing compressor can be regarded as wear-free. The dominant mechanism is expander blowby due to the wear of the bearing of the displacer. Blowby reduces the efficiency of the cooler, until the performance drops below the specification threshold. This is a wear-related mechanism. All the other known mechanisms are randomly occurring, of which the occurrence is mitigated by design, production procedures, or handling instructions. The chance of such a random failure occurring is minimal, provided that the cooler is designed with sufficient margins.

Blowby along the displacer due to wear is a time-dependent phenomenon. The wear of the bearing means that the clearance gaps increase, and leakage increases. A first-order approximation of this effect is described by Archard's law, $V_w = k_w F s$, with V_w the wear volume, k_w the wear coefficient, F the normal force, and s the distance travelled. This equation states that the wear volume depends on the properties of the wearing materials, the load which acts on the bearing, and the time the bearing is used.

The variables that can be affected and optimized are thus the materials properties, the distance travelled, and the load on the bearing. The materials used for these bearings are already state of the art. The distance travelled, determined by the operating frequency and the amplitude of motion, is fixed by the thermodynamic design of the cooler. That leaves the reduction of the load of the bearing as the main variable to be optimized.

This load has been analyzed in detail. There were found to be two main contributors: gravity and non-axial reaction forces of the displacer suspension. It was found, by measuring the reaction forces, that they can be up to 5% of the main axial spring force. The setup, shown in Figure 2, consists of a stationary part and a moving part (driven by a flexure-bearing suspended actuator). With manipulators, the alignment between both parts can be changed. With this setup, the implications of the design and tolerances of the bearing suspension could be easily validated without lengthy tribological or lifetime testing. Using it as a design validation tool, a displacer suspension with minimal radial force was designed. It was found that a reduction of more than a factor 5 was realized, directly decreasing the bearing load and thus increasing the availability of the cooler.

Lifetime verification

The optimized suspension was tested on the same test setup as shown in Figure 2. It was found that the radial forces were indeed minimized. To verify the improvement under actual conditions, lifetime tests were initiated. This was done by placing four coolers in the lifetime test setup at Thales Cryogenics. These coolers are operated 24/7 at a representative input power and inspected at regular intervals for performance. In addition, six coolers were tested by the customer.

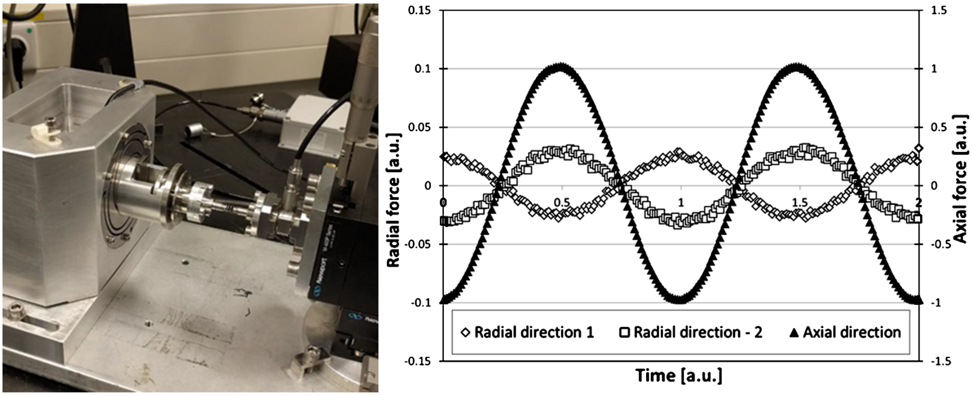

Figure 2. Measurement setup for spring reaction forces (left), and spring forces in three axes (right).

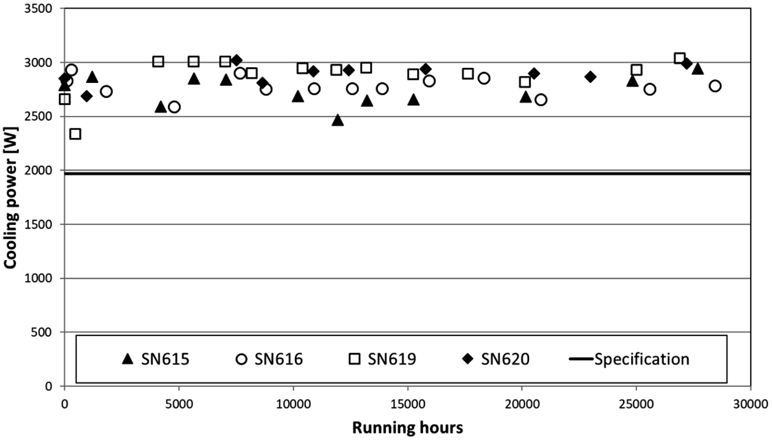

Figure 3. Lifetime test results of 4 LSF9589 coolers running in a controlled environment. The coolers are inspected at regular intervals and measured for performance. None of the coolers shows any degradation of performance.

Results of the four coolers in the lifetime lab setup are shown in Figure 3. Each of the coolers is inspected at regular intervals, and measured for performance. The performance plotted in Figure 3 is the cooling power at 77 K tip temperature, 80 W input power, and 23°C ambient temperature. The four coolers combined have gathered well in excess of 100,000 hours, and none of the coolers shows any degradation of performance. This data confirms the improved lifetime of the coolers.

In parallel with the lifetime test results, field tests were also conducted by the customer. Initially, a single system was put in operation in a high ambient and high humidity environment in Thailand. A cryogenic payload consisting of 6 LNA units with 12 RF IO interfaces was cooled. The results of 2 years of continuous operation are shown in Figure 4 below. It can be seen that the input power to the cooler, required to maintain 77 K tip temperature, seems to increase. Also, during the operation an increase in the vacuum pressure was observed.

Following this test, five more coolers were placed in operation in integrated modules such as shown in Figure 1 [4,5]. These five units have accumulated more than 80,000 hours of combined running hours. One of these coolers showed a similar increase of input power as the first unit. With re-pumped vacuum, the cooler showed no degradation compared to initial performance. At present, it is therefore assumed that the increase in power draw of the fielded unit in Thailand should be attributed to vacuum degradation rather than cooler degradation.

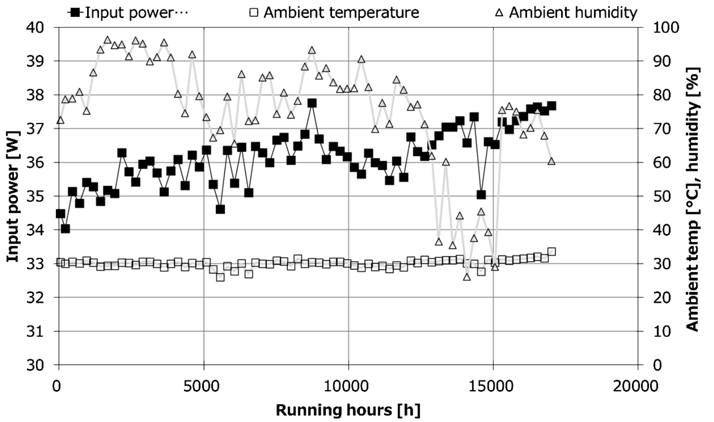

Figure 4. Lifetime field test results of 2 years continuous operation of an LSF9589 cooler with 6LNA's and 12 RF feedthroughs, operating at 77 K tip temperature.

HIGH-POWER, HIGH-AVAILABILITY STIRLING COOLER LSF9340

In the previous paper [1], we have presented the optimization of the 20mm LSF9340/9350 cooler for lower tip temperatures. In that version, we had not yet implemented the upgraded displacer suspension required for high-availability. That will be presented here.

The updated version of the cooler as presented here is different from the cooler that was presented previously. Instead of partially optimizing for performance and efficiency increase at lower tip temperature, this cooler was optimized for maximum cooling power at 77 K. The expected ambient temperatures are between room temperature and 40°C, which is also the temperature range in which the cooler is optimized. The goal is the maximize the cooling power, rather than coefficient of performance or efficiency. Optimization is thus aimed at increasing the allowable input power before maximum amplitude limits are exceeded.

Because the displacer suspension is to be changed, we have three variables available for optimization; the fill pressure, drive frequency, and suspension stiffness. In order to find the optimum configuration, a systematic series of performance measurement was performed, varying the drive frequency, fill pressure, and suspension stiffness. The maximum input power is the power at the cooler can be safely operated without moving components hitting the end stops. Cooling power is measured at this maximum input power.

The trade-off decisions that can be made based on such an optimization are indicated in Figure 5 and Figure 6. In Figure 5, the measured cooling power at a fixed input power of 100 W, 77K tip temperature, for one fixed displacer suspension is shown. Three curves are plotted for three different fill pressures. This is a typical optimization for efficiency. For each fill pressure, a distinct optimum drive frequency is found. A higher fill pressure needs a higher drive frequency and vice versa. The total optimum efficiency is reached with the middle curve, where the optima for compressor and cold finger efficiencies coincide.

In Figure 6, the measured cooling power at the maximum safe input power is shown. Each measurement point shown is thus measured at a different input power. In this case, the highest cooling power can be reached with the higher fill pressure. This is to be expected, because at higher fill pressure and drive frequency, the amplitude of the pistons can be lower for the same mechanical power.

These two graphs show only one configuration of displacer tuning. A different suspension tuning frequency yields a different set of curves. An overall optimum was chosen with the highest overall cooling power. This tuning was implemented in a cooler redesign, which is shown in Figure 7. This updated cooler was qualified in early 2020, and is currently finalizing the production ramp-up phase.

The resulting cooling power is shown in Figure 8, compared to the original configuration. In the overlapping region, the performance and efficiency of the high-availability upgrade and existing configuration are quite comparable. However, the optimized tuning yielded a maximum input power increase from 170 to 215 W (+30 %), giving approximately 20 % overall higher cooling power.

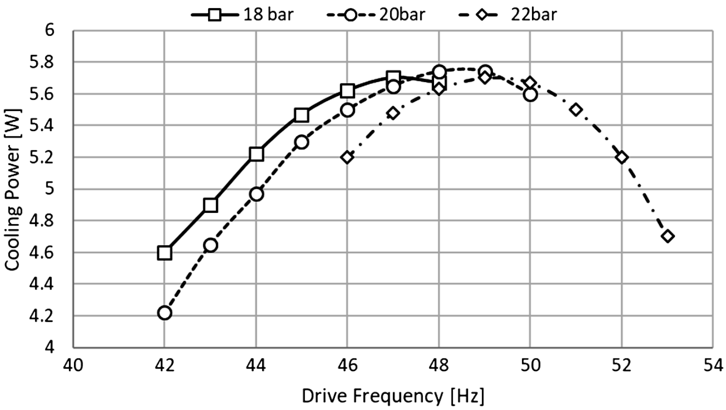

Figure 5. Example of the optimization of the cooling power of the 20 mm Stirling cold finger. The measured cooling power is plotted as a function of drive frequency for three different fill pressures. Tip temperature is 77 K, ambient temperature is 23 °C. input power is 100 W.

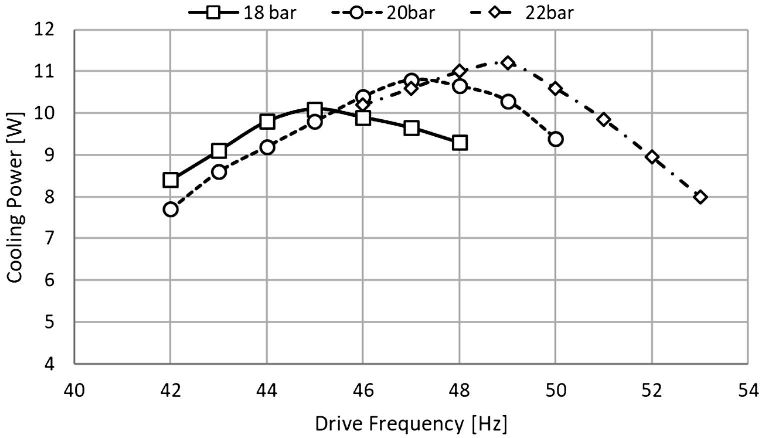

Figure 6. Same optimization as in Figure 5, but this time at the upper safe limit of input power. This graph thus shows the maximum attainable cooling power with this configuration for each fill pressure and drive frequency.

Figure 7. Photograph of the optimized LSF9340 cooler.

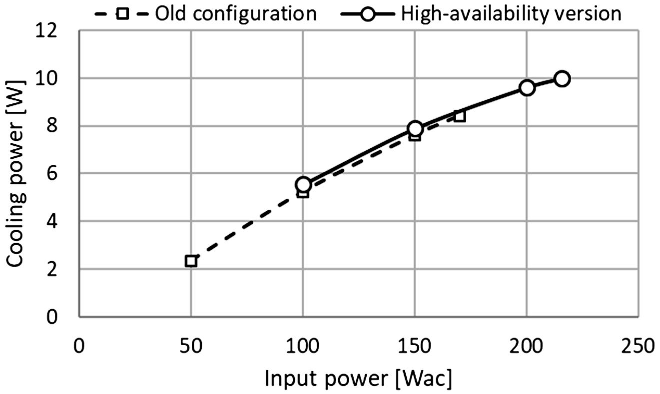

Figure 8. Measured performance of the existing configuration and the high-availability configuration. In this graph typical cooling power at 77 K tip and 23°C is plotted as a function of electrical input power. Data is the average cooling power as determined with acceptance test measurements.

Previously, we had presented the updated tuning specifically for low tip temperature operation. That re-optimization has not yet been done for the high-availability version of this cooler. However, experimental verification has shown a cooling power in excess of 2.5 W at 47 K tip temperature for this cooler.

COOLER AVAILABILITY – STIRLING VERSUS PULSE-TUBE

The two high-availability Stirling coolers as presented in this paper both represent a significant improvement in terms of availability compared to existing configurations. The improvement for the smaller LSF9589 is successfully being verified by lifetime and field tests; the bigger LSF940/60 is undergoing similar tests but does not yet have a significant number of hours accumulated. With the improvements, the expected availability will be extremely high. The coolers are designed for 98 % of availability after 5 years, which is comparable to the reliability of pulse-tube coolers.

However, there remains a fundamental difference between Stirling- and pulse-tube reliability. The main failure mechanism of a Stirling 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 10's 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. The amount of failures relative to the entire installed base of coolers is so small, that a statistical determination of lifetime or shape factors is not meaningful. Only a handful failures are known that can be attributed to the cooler itself, and all of these are traced back to aspects like process failures or problems with a specific batch of supplied components. The root causes of these all have been resolved. All of these failures can be considered 'early failures' or 'infant mortality.'

The availability of pulse-tube coolers can, however, be estimated by considering the installed base of coolers. We have started regular series supply of our LPT9310 pulse-tube cooler in 2006. For nearly all of these coolers, the usage profile is known, and can be used to estimate availability.

The following numbers are known:

- Delivered since 2006: ~2500 coolers
- Accumulated running hours in the application: 96,000,000
- Number of coolers operating > 5 year: ~1100
- Number of coolers operating > 10 years: ~350

A lower bound for the availability after a number of years can be estimated from these numbers. The availability after m years is better than $1\text{-}1/n_m$, with n_m the number of coolers running after m years. So, the availability of LPT9310 pulse-tube coolers is expected to be better than 99.9 % after 5 years and 99.7 % after 10 years. Both numbers are based on a fully random failure probability. These numbers show a significant improvement over previously published numbers [6], because of the increased number of operating hours in the installed base.

It can thus be concluded that, despite the very high availability and reliability of the new generation of Stirling coolers, the pulse-tube cooler is still the type of cooler to use in applications where extremely long lifetimes and low failure probability are key.

CONCLUSION

In this paper, updates on the High-Availability Stirling cooler range are presented. The initial development of this cooler family started with the LSF9589 (12mm diameter Stirling cold finger). That model has now collected a significant amount of operating hours in lifetime testing both in the lifetime test lab as well as in the field.

The high-availability Stirling cooler range was expanded with a 20mm, high power variant. Together with the implementation of the new displacer suspension, the cooler was re-optimized to deliver more cooling power at 77 K than the conventional version. This gives an increase in maximum available cooling power of 20 %.

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 coolers is comparable to that of pulse tubes. It was also shown that, 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.

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