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ABSTRACT

Thales Cryogenics (NL) and Thales Cryogenie (F), formerly known as Signaal Usfa and Cryotechnologies, closely co-operate in the field of production and development of linear and rotary cryocoolers. Over the past years, Thales Cryogenics has developed a complete range of long life Stirling cryocoolers with flexure bearings. In this paper the main design features of the flexure bearing compressor are revealed and their importance is explained.

Currently, a complete range of flexure bearing cryocoolers is fully qualified and ready for serial production. With these cryocoolers, which are available in slip-on configuration as well as IDCA (Integrated Detector Cooler Assembly), up to 6W @80K cooling power can be obtained. Also a pulse tube cryocooler with a specified cooling power of 500 mW @80K has been developed and is ready for serial production.

Two specific production machines have been developed and introduced in the production line. With this equipment Thales Cryogenics has been able to further improve the quality and reproducibility of its coolers.

Up to now, several flexure bearing cryocoolers have been built and integrated in various new commercial and military applications requiring long life cryocoolers. Besides this, Thales Cryogenics is active in several space applications in co-operation with Air Liquide/DTA.

DESIGN OF THE FLEXURE BEARING COMPRESSOR

It is well known by now that the only way to achieve long lifetimes with Stirling cryocoolers is by avoiding contact between the piston and cylinder inside the compressor. The most efficient way to achieve this is by introducing flexure bearings which fully support the piston mass at the front and back side with high radial stiffness.

However, many other parameters which determine the reliability of a cryocooler (e.g. outgassing of components, presence of other failure critical parts) are equally important to consider and are often neglected.

Thales Cryogenics has been working since 1997 on the optimization of a flexure bearing compressor taking all these critical parameters into consideration.

In this paragraph the design of the flexure bearing compressor and the motivation behind some of the choices which have been made in the design are summarised.

Flexure Bearing Design

The final design of the flexure bearings is a result of numerous Finite Element Modelling (FEM) calculations. With in-house developed flexure design software we have been able to compare many different flexure design configurations by performing both linear and non-linear calculations.

To verify the calculations, the maximum stress levels allowed in the design have been tested in practice by performing lifetime tests on many flexures at extended stroke. Data from these lifetime tests at component level have given us a clear view on the maximum stroke which can be achieved within a certain compressor outer diameter. In the final flexure bearing design, of which a photograph is shown in figure 1, a safety margin of 50% has been taken into consideration with respect to the maximum peak stress level at which failure can occur.

Furthermore, the flexures have been designed in such a way that only four (4) flexures are required to support each piston. These flexures do not only have a high stiffness in radial direction to support the moving mass, but by choosing a large flexure thickness, also the axial spring stiffness is relatively high. The reason for this design choice is that this makes the pistons insensitive for piston drift (change of the mid position of the pistons during operation). At the same time the axial spring stiffness of both the flexures, in combination with the gas-spring, is chosen in such a way that resonance is obtained with the moving mass inside the compressor.

With the current flexure design applied in all flexure bearing coolers the maximum stroke of the pistons is independent of the orientation of the compressor. An acceleration of more than 15g is needed to make the pistons hit their internal end-stops. For most space applications this means that a launch lock mechanism is no longer required for these coolers.

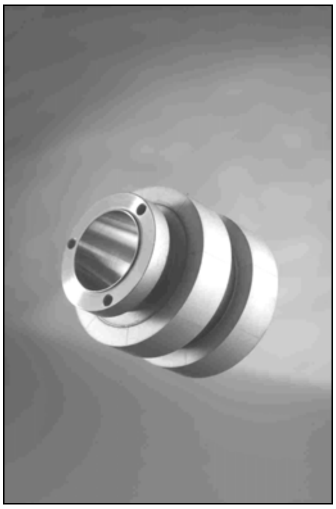
The two flexures at each piston end are manufactured as a sub-assembly in a so called “flexure pack”. In figure 1 also a photograph of a complete flexure pack containing the two flexures is depicted. In this sub-assembly the two flexures are connected to inner and outer mounting rings by means of laserwelding. Fixation of the flexures to the mounting rings by welding is essential to ensure that the alignment of the flexures in the compressor is not disturbed when the cooler is submitted to vibrations.

In fact, each part inside the compressor must be fixed so that small displacements in radial direction (even displacements of only a few microns) are impossible. In the final design of our flexure bearing compressor, each individual component is fixed by means of laserwelding. This has strong advantages compared to more conventional fixation methods using loctite, especially in serial production.

Moving Magnet Linear Motor

The main difference between our flexure bearing compressor design and that of most other companies manufacturing compressors for linear Stirling cryocoolers, is the fact that we use a moving magnet linear motor to drive the pistons, with coils located outside the pressure vessel containing the working gas. In figure 1 photographs of the magnet and coil assembly of the LSF 91xx cryocooler family are depicted.


(a)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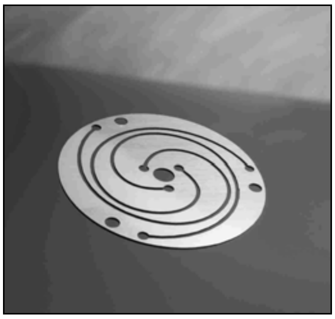
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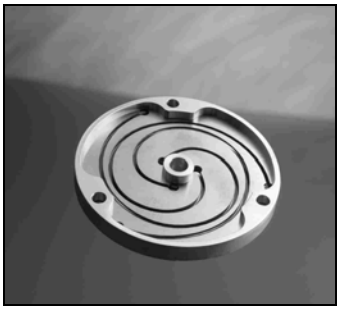
(d)

FIGURE 1. Most important parts of moving magnet flexure bearing design
(a) coil assembly (b) moving magnet (c) single flexure (d) flexure pack

The magnet circuit is achieved by two rings of permanent magnets, magnetised in radial direction, connected to an inner stator. This magnet assembly is directly connected to the piston and suspended at both ends by flexure bearings in the compressor. In this way the magnetic flux circuit for each moving piston is enclosed within the flexure bearings, which allows the flexure bearing outer diameter to be as large as possible.

The coil wires are wound on a coil-holder which is part of the pressure vessel containing the working gas. This means that the coils are outside the pressure vessel which offers some important advantages.

First of all, the fact that the coils are no longer moving means that flexible leads are no longer necessary to supply current to the coils. Absence of these components simplifies the compressor design and assembly and reduces the compressor length.

As the coil insulation consists of synthetic materials which can absorb moisture, bake out of components and curing of the cooler under high vacuum at elevated temperatures is probably the most critical process in the cooler production when the coils are located in the working gas environment. With the removal of the coils from the working gas, the most important outgassing component is removed from the helium gas environment inside the cooler. This reduces the risk of gas contamination during the life of the cooler.

Finally, the fact that the coils are located outside the hermetically sealed compressor means that also glass feed-throughs are no longer required. Under extreme temperature shocks and severe mechanical stresses on the cooler glass feed-throughs are known critical components which can crack resulting in gas leakage.

All these advantages have lead to the conclusion that for a high reliability cryocooler moving magnet technology in combination with flexure bearing suspension is the best solution to guarantee long lifetimes.

LSF CRYOCOOLER FAMILY: A COMPLETE PRODUCT RANGE

With one basic design of flexure bearing compressor we have been able to generate a complete new range of flexure bearing cryocoolers. By changing only four parts inside the compressor it is possible to optimize the compressor for different sizes of Stirling- or pulse tube coldfingers. In the following paragraphs the complete product range of flexure bearing cryocoolers which is currently available at Thales Cryogenics is described in detail.

LSF 91xx Stirling Cryocoolers: 0.5-3W @80K

In the LSF 91xx cryocooler range four main types of Stirling cryocoolers have been defined, based on the four most common coldfinger diameters. In figure 2 below four graphs have been depicted showing the specified cooling performance of these coolers at different ambient temperature levels. As can be calculated from these graphs the specified overall efficiency increases from about 1.5 % to 3 % when increasing the coldfinger diameter from 5 mm to 13 mm. This is mainly due to an increased efficiency of the coldfinger when going to larger diameters.

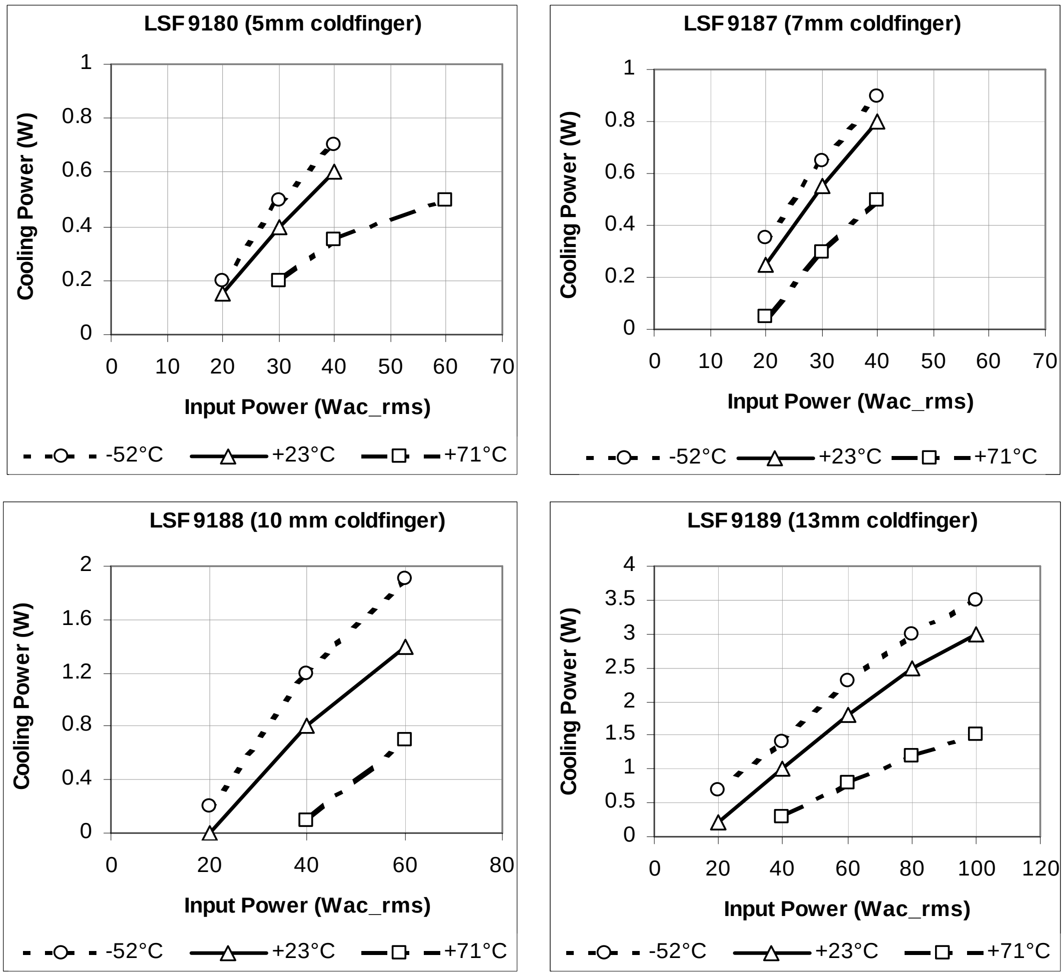

FIGURE 2. Specified cooling performance at different ambient temperature levels for four coolers of the LSF cryocooler family

FIGURE 3. Photograph of the final flexure bearing coolers LSF 9180 (5mm cold finger) and LSF 9188 (10mm cold finger)

In figure 3 above a photograph of two coolers from the LSF 91xx cryocooler family is depicted. The final definition of the mechanical interfaces (e.g. flange on the coldfinger, splitpipe length and bending) are strongly dependent of the application and are defined in close co-operation with our customers. Besides slip-on coolers, also standardized IDCA configurations (e.g. SadalI) are available.

LSF 9320 Stirling Cryocooler: 6W @80K

Based on growing demands from the civil market for larger cooling capacities an upscaled version of the LSF 91xx cryocooler has been developed. With our in house developed Stirling simulation software we have calculated that for cooling power levels of 6-8W @80K, a 20 mm coldfinger diameter is required to achieve maximum efficiency. In figure 4 below the impact of the coldfinger diameter on the efficiency is shown.

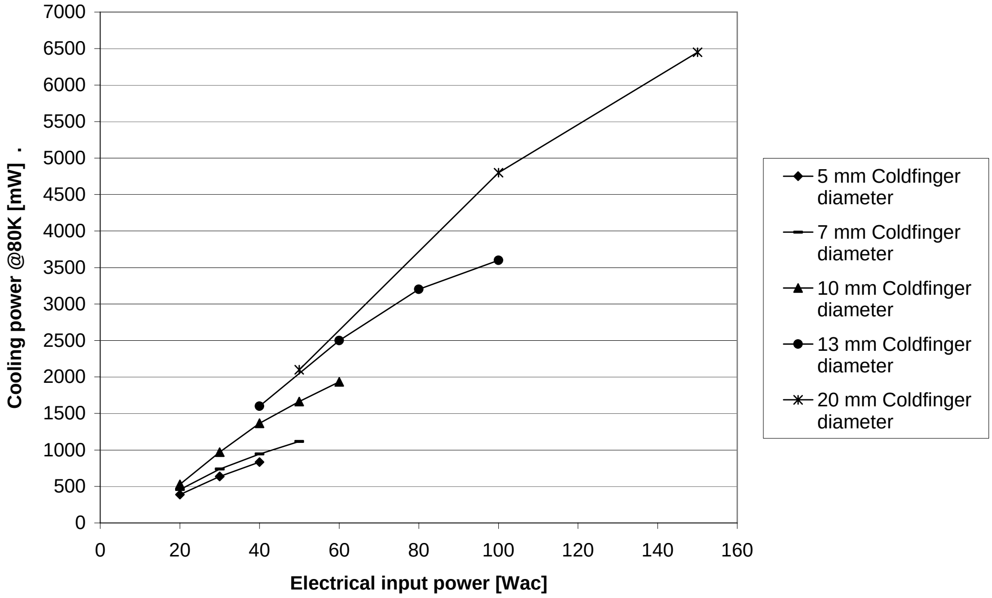

FIGURE 4. Impact of the coldfinger diameter on the efficiency of the cooler (measurement results @23°C)

In this graph the measured cooling power at different electrical input power levels is plotted for different types of coolers available at Thales Cryogenics. As can be seen, the efficiency as well as the maximum cooling power increases with increasing coldfinger diameter. To drive the 20 mm coldfinger an upscaled version of the moving magnet flexure bearing compressor has been designed. This compressor, with a maximum total swept volume of 12 cc, is matched with the 20mm coldfinger to obtain resonance conditions and thus maximum overall efficiency.

Up to now several prototypes of LSF9320 coolers have been built and integrated in various applications. Thales Cryogenics has also planned to further develop this cooler for use in Space applications. For these applications a redesigned version of the 20 mm coldfinger has been developed with flexure bearings which support a pneumatic driven displacer. First test results have shown that with this coldfinger the efficiency of the LSF 9320 cooler is further improved by about 10-20%.

LPT 9110 Pulse Tube Cryocooler: 500 mW @80K

Thales Cryogenics also has developed a pulse tube coldfinger, driven by a flexure bearing compressor, which has been optimized for the pulse tube void volume. With this combination, which is referred to as

LPT 9110, a cooling power of 650 mW @80K and a minimum temperature of 65 K have been measured. The electrical input power to the cooler for this performance is 60 Wac.

The pulse tube is U-shaped, inertance type and single inlet. We have learned over the past year that a double inlet pulse tube is capable of achieving even better performances, but the dc-flow effect which is always present in double inlet pulse tubes make this configuration unsuitable for serial production and use under various ambient temperatures.

We have built several prototypes according to the optimized design and found that with the final design configuration, combined with the flexure bearing compressor, a very stable performance level is achieved. The LPT 9110 cooler, with a specified maximum cooling power of 500 mW @80 K at room temperature conditions is ready for serial production.

For a specific commercial application requiring ultra low induced vibrations, we have developed a complete pulse tube cryocooler driven by cooler drive electronics with active vibration control. With this cooler we have been able to reduce the induced vibration to a level below 0.02 Nrms in all cooler directions.

QUALIFICATION TESTING AND LIFETIME TESTING

The LSF 91xx coolers have undergone an extensive qualification test program including extensive testing under different ambient temperature conditions and the following shock and vibration tests:

- Repetitive Shock (operating) : IEC 68-2-29 Test Eb
- Shock (operating) : IEC 68-2-27 Test Ea
- Vibration, Random (operating) : IEC 68-2-36 Test Fdb
- Vibration, Sinusoidal (operating) : IEC 68-2-6 Test Fc

Besides these MIL-standard tests one cooler has been built in a centrifuge where it has been running for 500 hours with accelerations increasing up to 10g working in radial direction on the compressor. These tests have verified that even with high side loads working on the moving mass inside the compressor, the flexure bearing suspension prevents wear of the pistons.

During the past two years, in total eight flexure bearing cryocoolers (LSF 91xx type) have been put in lifetime test. These coolers are continuously running at room temperature conditions at approximately 80% of their maximum input power level. Under these conditions the lifetime tests can be considered as accelerated lifetime tests, because in practical applications the coolers will always be running at a much lower input power level during steady state conditions.

Our first prototype flexure bearing cryocooler currently (July 2001) has reached more than 20,000 operational hours and still shows no signs of degradation. Four LSF 9188 coolers have been put in lifetime test at different dates beginning of last year and have so far accumulated lifetimes between 9,300 hours and 11,700 hours. Two of these coolers have been put into lifetime test after successfully completing the qualification test program mentioned above.

In addition, three more flexure bearing coolers (LSF 9180 type) have been put in lifetime test end of last year and beginning of 2001. These coolers have accumulated lifetimes varying between 3,900 hours and 7,500 hours so far.

Lifetime tests on our high capacity flexure bearing cooler (LSF 9320) are planned to start during the second half of 2001.

PRODUCTION CAPABILITIES AT THALES CRYOGENICS

During the past year, Thales Cryogenics has acquired two new production machines which have been specifically designed by external companies in close co-operation with our production engineering department.

First of all a dedicated machine for the process of stacking of gauzes in a displacer tube has been developed and installed in the cryocooler production line. Below, a photograph of this machine is shown.

With this machine each individual piece of gauze is cut after which loose wire ends are blown away. Then the gauze is transported to a separate placement unit and placed into the displacer tube. The force with which the gauzes are pressed onto each other is controlled and after each gauze has been placed the stack height is measured and automatically checked.

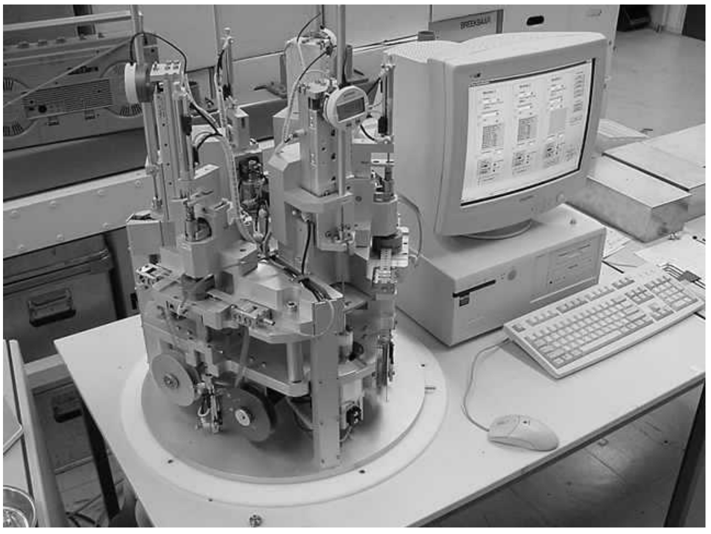

FIGURE 5. Photograph of the new gauze stacking machine at Thales Cryogenics.

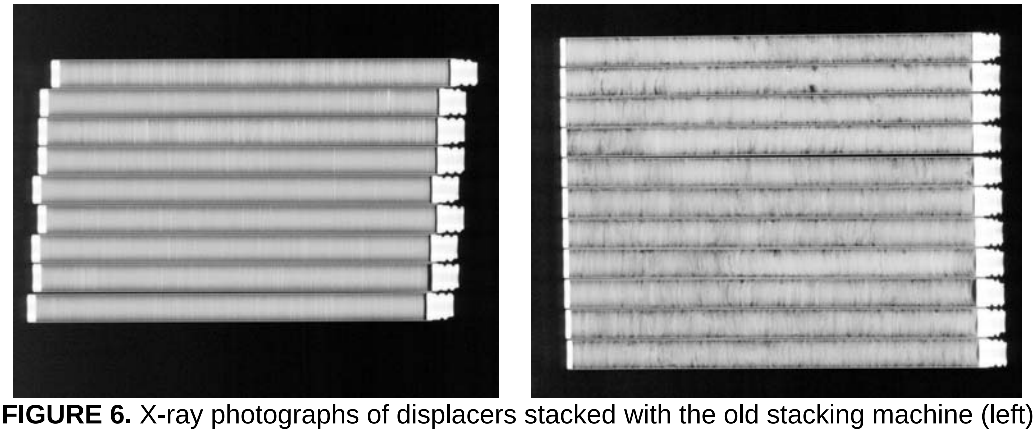

FIGURE 6. X-ray photographs of displacers stacked with the old stacking machine (left) and new stacking machine (right)

In figure 6 two X-ray photographs are depicted which clearly show the more uniform gauze stacking obtained with the new gauze stacking machine. With this machine we are currently able to reproduce displacers with a spread of only about 10 gauzes, which is about 1% of the total number of gauzes stacked in the tube. As a result of this we have been able to further reduce the spread in cooling performance of our cryocoolers leaving the production line.

Besides this, also a hydrostatic lathe has been installed in a temperature controlled room in our production department. With this lathe piston and displacer bearings are currently machined with an accuracy of < 1 m over the complete length of the piston. In practice this means that we are able to machine pistons directly to the correct diameter to match with the cylinder in which it will be running.

With this machining accuracy, we have been able to further reduce the initial gap between the pistons and cylinder. This has resulted in a slight increase of cooling performance as well as a more constant production output with significantly less spread in cooling efficiency.

CONCLUSIONS

Thales Cryogenics has continued its development of flexure bearing cryocoolers, which has resulted in a complete range of Stirling and pulse tube cryocoolers currently available, with cooling capacities up to 6W @80K.

The flexure bearing compressor design has flexure bearing suspension at the front- and back-side of the piston and has a moving magnet linear motor with coils outside the Helium gas. Combined, these factors lead to a compact and affordable cryocooler with extreme high reliability.

Thales Cryogenics, which has its roots in military applications, is currently introducing its flexure bearing cryocoolers in more and more civil applications. Besides this, the LSF cryocoolers are currently introduced in several space applications.

For more detailed information on our products and capabilities, please visit our web site: www.thales-cryogenics.com.