Development of a 15 W Coaxial Pulse Tube Cooler

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ABSTRACT

In the recent years Thales Cryogenics has achieved good cryogenic performance results with its one- and four-watt pulse tube coolers operating around 80 K, which are currently in full serial production. These coolers consist of compressors that are based on well-proven and highly reliable flexure bearing technology, and pulse-tube cold fingers that are based on a CEA/SBT design. This design has been further optimized by Thales. In 2007 Thales has developed and tested the even more powerful LPT9710 coaxial pulse tube cooler that has proven to produce a cooling power of at least 15 W at 80 K.

Advantage of a pulse-tube cooler in this cooling range is the absence of a relatively high moving mass, present in a Stirling cooler with similar performance. This moving mass results in high forces and consequently high induced- vibration levels at the coldfinger mounting position and has a negative impact on cooler reliability. The LPT9710 is a cost-effective, low–vibration, and very high-efficiency pulse-tube cooler that is able to reach high cooling powers and low temperatures with a single-stage cooler. Temperatures down to 40K have been measured, without optimization for this operating temperature range.

This paper describes the trade-offs that have been considered in the design phases of the compressor and the pulse tube. Design optimizations of the complete pulse-tube cooler will be presented as well. An overview of the test results, the status of the qualification program and the resulting specification of this pulse-tube cooler will be given. The high cooler efficiency will be outlined in more detail and will be compared to other split-Stirling and coaxial pulse-tube coolers. Finally, future development areas that have been made available by this new compressor and pulse tube will be discussed.

INTRODUCTION

THALES Cryogenics BV has been designing and building pulse-tube refrigerators (PTRs), initially with an in-house developed U-shaped PTR. Later, coaxial PTR's have been developed in cooperation with CEA/SBT (Commisariat à l'energie atomique, service des basses temperatures). This has led to two production models, the LPT9510 and LPT9310, shown in Figure 1, with cooling powers of 1 W and 4 W at 80 K, respectively [1][2].

Both PTR's use flexure-bearing compressors with long Mean Time To Failure (MTTF). The dual opposed piston compressor has low vibrations, and the flexure bearing technology yield long lifetime. This, together with the absence of moving parts in the cold finger, makes the PTR

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Figure 1. The LPT9510 (foreground) and LPT9310 coaxial pulse-tube coolers.

the cooler of choice in applications where long lifetime and low vibrations are very important, or in situations where large masses are connected directly to the cold finger. They are typically used in high-end civil applications, such as electronic equipment and sensors for analysis and diagnostics.

The current production versions of the coaxial pulse tubes are industrialized versions of the original prototypes. They are in full serial production. Recently, an in-house development has led to further optimization of these systems for improved performance, efficiency, and manufacturability [3].

This paper further describes the development of a new member of the LPT coaxial pulse-tube family, the LPT 9710. This large pulse tube is capable of producing more than 15 W of cooling power at 80 K. This new PTR is completely designed and built at THALES. It is driven by a newly designed compressor. The development of this 300W PdV compressor is described in the next section of this paper.

The design and test results of the pulse-tube is described next, followed by the final specification of the entire product. The paper finishes with the identification of future development areas involving this compressor and pulse tube.

COMPRESSOR DESIGN

THALES Cryogenics has extensive knowledge and experience in designing and building flexure-bearing compressors [4,5]. This knowledge was used in the development of the new, larger compressor. The objective with respect to performance was to deliver 300 W of mechanical power (often referred to as PdV-power), with a total compressor efficiency of at least 75 %. This would make the maximum electrical input power 400 W.

The design process started with a concept study of different linear motor concepts. Given the high requirement for efficiency, and other constraints such as dimensions, weight, and swept volume, a moving magnet-type linear motor was chosen. Because of the large magnetic field gradients and changes, it was necessary to fully optimize components that are part of the magnetic circuit for minimum magnetic losses such as eddy current and hysteretic losses. Together with the Joule-losses, these losses determine the overall efficiency of the compressor.

Figure 2. The large compressor (300 W PdV) in part of its heat sink.

The flexure bearings were optimized for performance, lifetime, and cost/manufacturability. Our dedicated (Algor©-based) design software was used for that.

Figure 2 shows a photograph of the new compressor. It is shown in the bottom part of its heat sink. To improve heat sinking and reduce mass, the outer housing is made of aluminum. Apart from the heat that is generated by the compressor itself due to its intrinsic losses, also a large part of the heat due to the mechanical power should be removed at the compressor.

Performance and measurements

Initial tests on the large compressor were done with a cold finger of the LSF9330, which is high-end flexure-bearing supported 20 mm Stirling cold finger. This allowed preliminary testing of the compressor before the LPT9710 pulse tube cold finger was available. The limiting factor in this case was the power level; the relatively small Stirling cold finger could only be tested up to 125W electrical input power, because this Stirling cold finger is designed to match a compressor that can produce significantly less mechanical power than the 9710 compressor.

Measuring compressor efficiency is only possible with a cold finger attached. The individual contributions to the total system efficiency can be determined using measurements of current, voltage, compressor stroke and other quantities. The compressor efficiency, when integrated to the LSF9330 cold finger, was above 80 %, which is well above the design goal of 75 %. Because the compressor was not designed to match with the Stirling cold finger, compressor losses were relatively high. When integrated to the LPT 9710 pulse-tube cooler, the compressor efficiency is thus expected to be even higher.

Thermodynamic performance is shown in Figure 3. The cooling power is plotted as a function of the cold-tip temperature. It can clearly be seen that the combination of the efficient Stirling cold finger with the large compressor results in a very efficient system. The total cooler efficiency of nearly 10 %, which is approximately 27 % relative to Carnot, is exceeding the performance of the state-of-the-art in split-Stirling cryocoolers [6,7]. More details about combining the new compressor with a Stirling cold finger can be found in the section 'Future developments'.

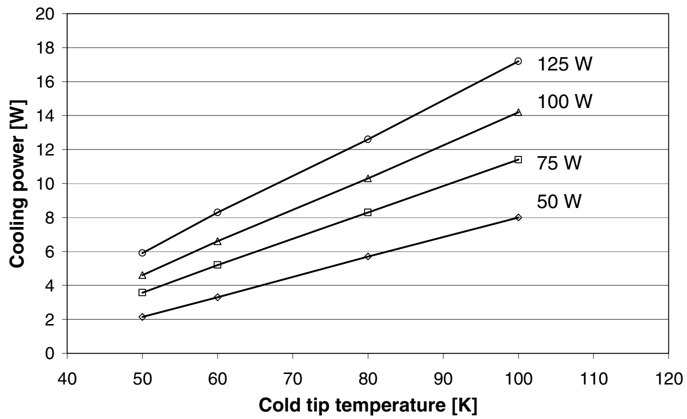

Figure 3. Cooling power of the LSF9330 driven by the 9710 compressor as a function of cold-tip temperature, for different electrical input powers.

PULSE-TUBE DESIGN AND OPTIMIZATION

The pulse tube was designed using the experience that was gathered during optimization of the 4 W pulse tube presented at the CEC last year [3], and with the result of the in-house developed pulse-tube simulation tool.

Given the large powers involved – both cooling power and input power – special attention was paid to heat transfer from and to the cooler. Similar to the compressor, the warm end of the pulse tube is made from high-grade aluminum. In the aforementioned optimization of the LPT 9310, it was found that an aluminum warm end leads to a significant increase in cooling power. Further optimization also included cost-efficiency. This experimental optimization included the study of the performance of the inertance tube, heat exchangers, and flow straighteners for different configurations. The optimization of the heat exchangers will be presented in the following section.

The inertance tube was optimized for maximum cooling power and efficiency, by changing its length and diameter. The consequent experimental optimization showed little influence between the different geometries, and will therefore not be further discussed in this paper.

The optimization of the flow straighteners did not show any opportunities for large performance improvement. Several options for constructional improvements were identified and included in the design. These are, however, not within the scope of this paper.

Heat exchanger optimization

Heat exchangers in cryogenic coolers are usually relatively complex components. Optimization leads to large surface areas and low pressure drop. This often results in designs with large numbers of narrow slits, which are produced using expensive manufacturing methods such as electrostatic discharge machining (EDM). Experience with the optimization of the LPT 9310 showed that it is possible to reduce the cost of the heat exchangers by using other geometries. In that particular case, the loss in performance was compensated for elsewhere in the system.

The standard configuration of the cooler uses slit-type heat exchangers in all positions. For the after cooler, where the heat of compression has to be removed from the system, we experimented with heat exchangers using holes instead of slits. The results are shown in Fig 4. It turned out that the decrease in cost did not outweigh the decrease in performance. It was therefore decided to keep using slit-type heat exchangers on the warm end of the cooler.

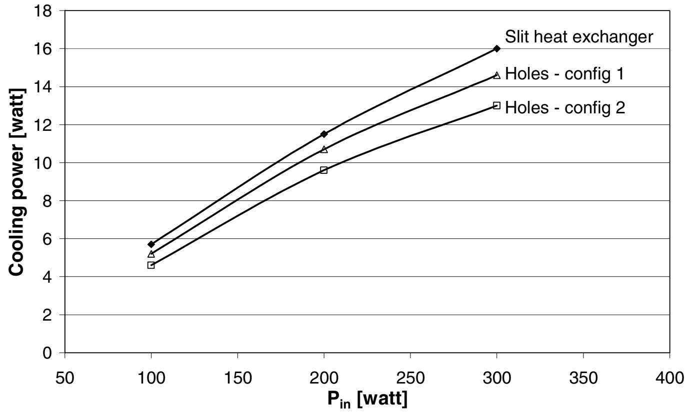

Figure 4. Measured cooling power versus electrical input power for the prototype pulse tube. The main difference between configuration 1 and 2 is the amount of holes.

A similar optimization was done on the cold heat exchanger. The results are shown in Fig 5. Both configurations are slit-type heat exchangers. The alternative configuration uses a different slit geometry. The reduction in cost would be caused by a reduction in the amount of EDM-time. The conclusion for the cold end is similar to that of the after cooler. The high heat load and cooling power, together with the requirement for optimum efficiency do not allow any compromises in the design of the heat exchangers.

PERFORMANCE QUALIFICATION AND FINAL SPECIFICATION

In this section, the final qualification of the 15 W pulse tube will be described. The qualification measurements were intended to determine the final specifications of the pulse tube. Performance measurements focus on the cooling power as a function of cold-tip temperature, electrical and mechanical input power, heat sinking temperature, and orientation.

In Fig. 6, the cooling power is plotted as a function of cold-tip temperature, for different electrical input powers, and a heat sinking temperature of 20°C.

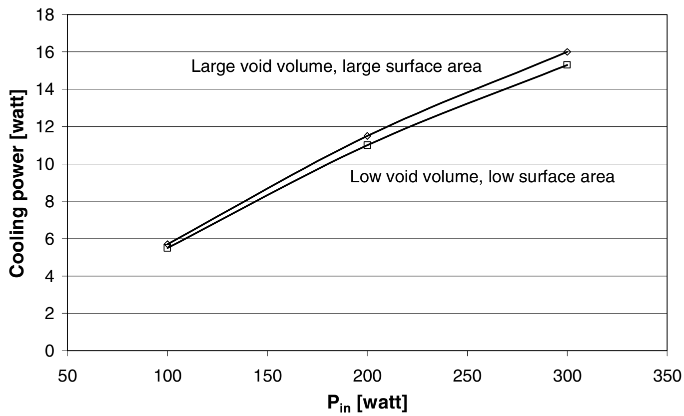

Figure 5. Cooling power versus electrical input power for two different cold heat exchanger configurations.

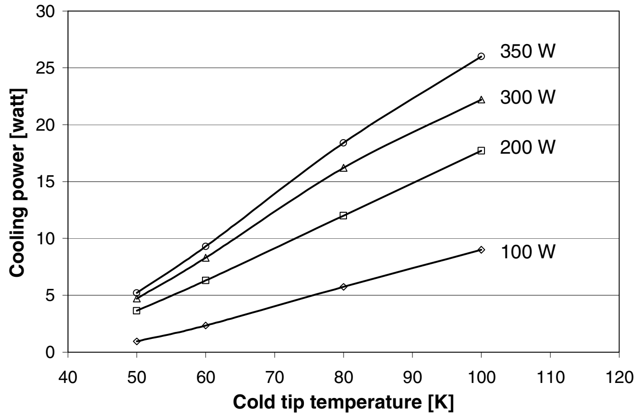

Figure 6. Measured cooling power versus cold tip temperature for different electrical input powers and a heat sink temperature of 20°C.

In Fig.7 the same data are plotted for a heat sink temperature of 45°C. For a heat sink temperature of 20°C, only 275W of electrical input power was needed to reach the specified 15 W of cooling power at 80 K. The total cooler efficiency is 5.5% or 15% of Carnot. For 45°C, 350 W of input power was needed to reach 15 W of cooling power at 80 K. One of the reasons for the high efficiency is the high compressor efficiency. Because the large compressor is matched to the pulse tube even better than to the LSF9330 cold finger, the compressor efficiency increased to approximately 85%.

Finally, the influence of the orientation of the pulse tube was characterized. The results are shown in Fig. 8. Similar to previous observations [2], the influence of the orientation is the largest in the 135° position. However, the influence is small, and only visible for low input powers. For input powers above 200 watt, the influence is negligible. This is the result of the strong gas flows in the pulse tube; because of those there is no opportunity for secondary gas flows to develop.

Finally, the performance of the LPT9710 is compared relatively to the current 4 W PTR (LPT9310), and the best performing PTRs available in the market today, i.e. the high end PTRs such as used in space applications. This comparison is shown in Fig. 9.

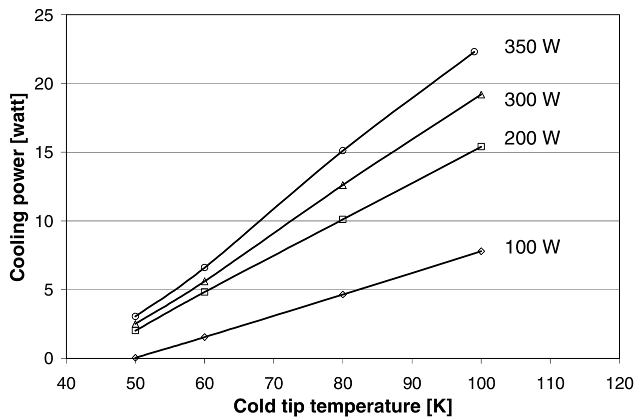

Figure 7. Measured cooling power versus cold tip temperature for different electrical input powers and a heat sink temperature of 45°C.

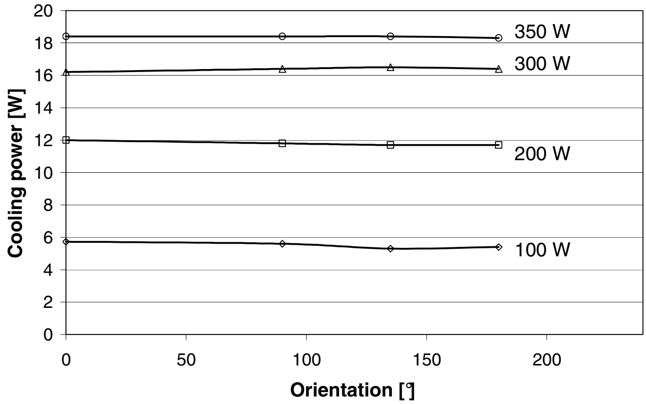

Figure 8. Measured cooling power at 80 K and 20 °C heat sink temperature versus orientation, for different input powers. The orientation of 0 °C corresponds to the cold end down.

In this figure, the specific power is plotted as a function of the cooling power. Specific power is the amount of input power that is necessary per watt of cooling power. In Fig 9, several lines are visible. Three lines represent coolers available at Thales Cryogenics, i.e. the standard version of the LPT 9310, a high-end version of the LPT 9310 with improvements described in [3], and the LPT9710. These are the solid lines with markers. The dashed line is the average of currently available high-end PTRs in the market [7]. These are coolers intended for space applications and are in single units at significantly higher price levels. As a reference, lines with constant Carnot efficiency are added.

It can clearly be seen that the efficiency of the LPT9710 is equal or better than that of the high-end PTRs. It is important, however, to realize that the LPT9710 is a different cooler than the other coolers in the graph. It is a higher power cooler with consequent higher mass and dimensions. This should be kept in mind in the quantitative comparison between the LPT9710 and other coolers in the graph.

The performance of the LPT9710 in terms of cooling power and efficiency is even better than commercial available split-Stirling cryocoolers of equivalent performance, and is therefore a viable alternative to such a cooler without the inherent high vibrations of a Stirling cooler, at the price of higher mass and volume.

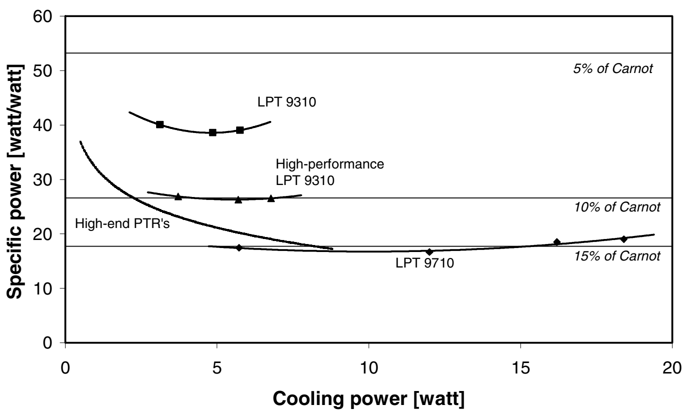

Figure 9. Specific power versus cooling power for the LPT 9310 and LPT 9710, compared to the currently best-available PTRs.

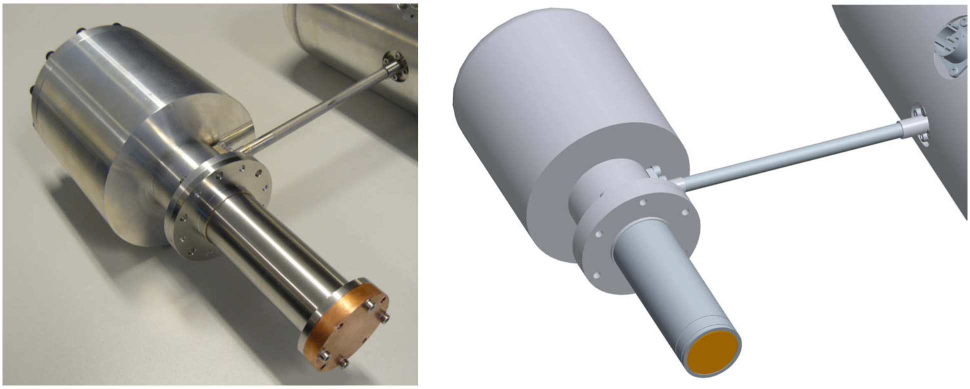

Figure 10. Photograph of one of the prototypes (left) and a 3-D rendering of the industrialized version of the coaxial pulse-tube cooler (right).

FUTURE WORK AND DEVELOPMENTS

The results presented in the previous section were obtained from the first prototypes of the new LPT9710 coaxial pulse tube cooler. The performance was determined and specifications characterized. The next step is to translate this design to an industrialized version, suitable for series production. This work is currently in progress. In Fig 10, a photograph is shown of the prototype version compared to a rendering of the industrialized version. The industrialized version has less flanges and seals. These are replaced by welds, thus minimizing the risk of leaks. Furthermore, the interface with the cold heat exchanger is changed into a more universal interface. As an added advantage, this reduces thermal mass and cool down time.

Both components of the LPT9710 cooler – the compressor and cold head – give sufficient opportunities for further developments. The current version of the cold head is optimized for maximum cooling power and efficiency at 80 K. It could, however, also be optimized for other temperatures. The regenerator could be further optimized for these temperatures by changing regenerator matrix composition, different gauzes, mixed gauzes, and other materials. Further optimization could also include high-end materials such as titanium, further reducing conduction losses and thus increasing cooling power at significantly lower cold tip temperatures.

The high-efficiency compressor itself is also a basis for further cooler developments. Given the success with the integration of a LSF9330 cold finger (see Fig. 3), expansion of the performance window could be obtained by combining the compressor with a Stirling cold finger. Such a cooler would be able to provide a cooling power of at least 35 W with 350 W electrical input power at 80K. In practice, cooling power would probably be even higher, because the efficiency tends to increase as absolute power and size increases [6].

CONCLUSIONS

In this paper, the newest member of Thales' coaxial pulse-tube cooler range was presented. This LPT 9710 is the largest cooler in this family, capable of cooling more than 15 W at 80 K. The design considerations were discussed, and it turned out that one of the most important aspects of optimizing such a cooler is to ensure maximum efficiency in the transfer of heat from and to the cooler.

The characterization of the cooler showed a cooling power of 15 W at 80 K, with 275 watt of electrical input power. The efficiency of the cooler, 5.5 % or 15 % relative to Carnot, is unprecedently high for a pulse tube cooler. Part of this is due to the high compressor efficiency of 85 %. This newly designed compressor was designed to deliver up to 300 W of mechanical power, which requires 350 W of electrical input power at the given efficiency. The high performance of the pulse tube and compressor give possibilities for further developments. There are no concrete results available yet, but coolers with lower cold-end temperatures or higher cooling powers could be the next step. The first step however was the industrialization of the LPT9710, which will be available in series production by the end of 2008.

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