Development of a Two-Stage High-Temperature Pulse Tube Cooler for Space Applications

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In the framework of a Research and Technology program co-funded by the French space agency (CNES), CEA/SBT is developing a high-frequency, two-stage pulse tube cold finger able to provide 2 W at 70 K on the second stage and simultaneously 6 W at 140 K on the first stage. This cooler is addressed to the cooling needs of detectors for low-Earth-orbit observation missions. To capitalize on other European efforts in the cryocooler field, this cold finger is designed to operate with the compressor developed under the ESA LPTC project. This compressor is able to provide around 120 W of PV power. A modular prototype of the pulse tube cold finger has been built, and the design of this prototype is presented together with our first experimental results. The effect of input power and rejection temperature is described.

INTRODUCTION

Two-stage coolers have been historically developed to achieve lower temperatures than single-stage coolers. For Earth observation, two-stage coolers that operate in the same temperature range (50 K-80 K) as single-stage coolers have been identified as a promising technology. They can be used with detectors operating at two different temperatures, or the first stage can be used to cool optics or electronics. The French space agency (CNES) has funded a research and technology activity in our lab to develop a two-stage pulse tube cold finger.

OBJECTIVES OF THE WORK

Under the framework of an ESA contract, we have developed—in partnership with Air Liquide and Thales Cryogenics—a Large Pulse Tube Cooler (LPTC) able to provide a cooling power of 2.3 W at 50 K with 160 W of electrical input power.[1,2] In order to benefit from the development and the qualification of this product, the idea was to develop a new pulse tube cold finger matched to the present LPTC compressor design. The objective of this two-stage pulse tube cold finger was to provide, simultaneously, 2 W of cooling power at 70 K, and 6 W at 140 K, when coupled to the LPTC compressor. The choice to link this development to an existing product led to some constraints in terms of operating pressure, mass flow rate, frequency, and input power. The nominal conditions for operating the LPTC compressor are described hereafter. The fill pressure is 30 bars, the swept volume is 6.3 cm^3, and the operating frequency is 57.5 Hz. The electrical input power is

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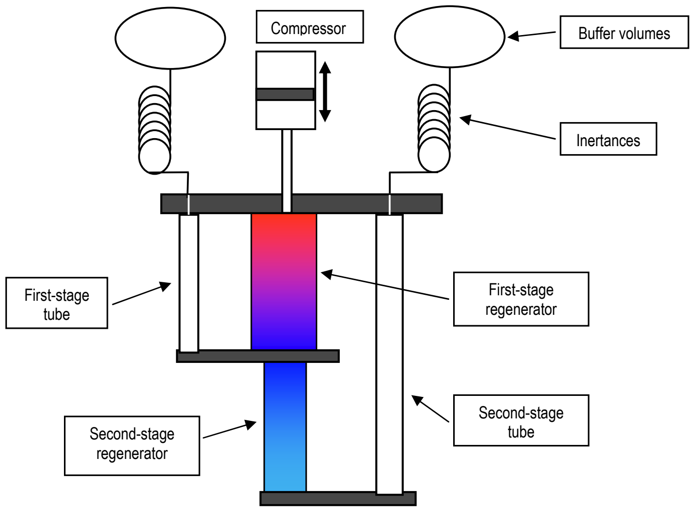


Figure 1. Scheme of two stage pulse tube cold finger.

160 W, which gives around 120 W of mechanical PV power to the gas. All these values were used for the two-stage pulse tube cold finger described below.

DESCRIPTION OF THE PROTOTYPE

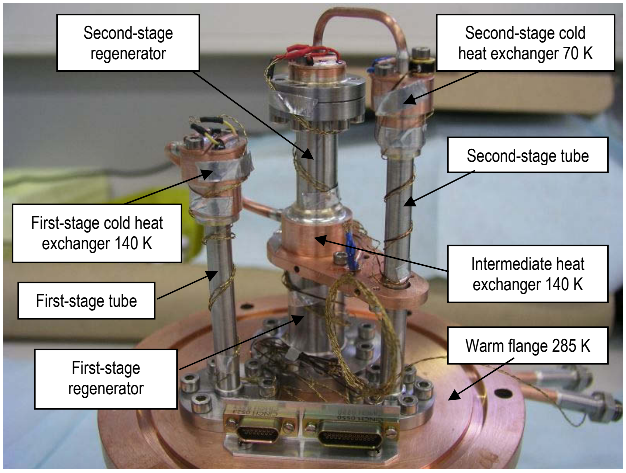
There are at least four different possible architectures for a two-stage pulse tube using only one compressor.[3,4,5,6] For our prototype, we decided to use the most widespread architecture used for low-frequency pulse tube coolers.[7,8,9] In this architecture, represented in Figure 1, regenerators of the first and second stage are put in series, and the hot ends of the pulse tubes of each stage are thermally coupled to an ambient-temperature heatsink. In this design, one part of the mass flow coming from the first regenerator goes to the first-stage pulse tube, whereas the other part goes through the second regenerator to the second-stage pulse tube. In this architecture the phase shifters are placed outside of the cryostat at ambient temperature. For this development, only inertances were used to do the phase shifting. These inertances are connected to two separate buffer volumes.

A versatile prototype has been designed and built. Most of the assembly has been made using screwed flanges or soft brazing to allow easy modification of the second-stage regenerator and the pulse tubes of both stages. One of the prototypes built during this development is represented in Figure 2. Heat exchangers located at pulse tube cold ends and between the regenerators are made by electro discharge machining in copper. Copper is also used for the main flange, which contains the heat exchangers for the warm ends of the pulse tubes and the first-stage regenerator entrance; these are also made by electro discharge machining. Regenerator walls and pulse tubes are made of thin stainless steel tubes. Regenerators are filled with stainless steel meshes. A copper shielding is clamped on the intermediate heat exchanger to reduce the radiation parasitic losses on the second stage as shown in Figure 2 (left). All the cold parts are wrapped with multi layer insulation (MLI).

The cold finger is equipped with heaters and thermometers on each stage. A Cernox thermometer is used on the second stage to give an accurate temperature for the ultimate temperature; platinum thermometers are used elsewhere.

OPERATING CONDITIONS

For this development, a new large compressor developed by Thales Cryogenics was used; it is referred to as the LSF97xx .[10] This dual-piston compressor has a swept volume of 21 cc and is able to provide more than 300 W PV power. Its efficiency is around 85%. The PV power reported in this paper is estimated by removing the Joule losses from the total electrical power (i.e., $PV=W-I^2R$).



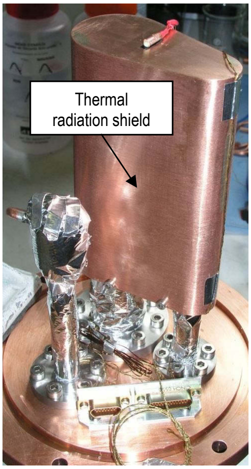


Figure 2. Two-stage pulse tube without (left), and with (right) the second-stage thermal shielding before MLI wrapping.

The warm copper flange is cooled to 285 K by a water cooling circuit. All the tests presented hereafter have been performed with a fill pressure of 30 bars and an operating frequency of 57.5 Hz. A view of the test bench is presented in Figure 3. The net cooling power is measured for the second stage on the cold heat exchanger of the pulse tube, and for the first stage, on the intermediate heat exchanger located between the two regenerators.

THERMAL TEST RESULTS

Cooling Map

Thermal tests were performed using different inertance tubes on the first and second stages. For each pair of inertances, described in Table 1, and for the various applied loads summarized in Table 2, the temperatures of the first and second stage were recorded. Figure 4 presents the best performance obtained for the three different pairs of inertances.

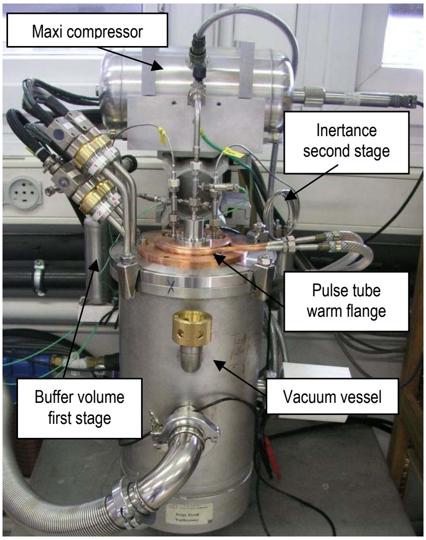


Figure 3. Test bench

Table 1. Pairs of inertances represented in the cooling map.

	Length of the inertance (Note: same diameter for all inertances)	
Pairs of Inertances	First stage	Second stage
#a	long	short
#b	long	long
#c	short	long

Table 2. Different loads tested.

Case	Load on first stage (W)	Load on second stage (W)
#1	0	0
#2	6	2
#3	6	0
#4	0	2

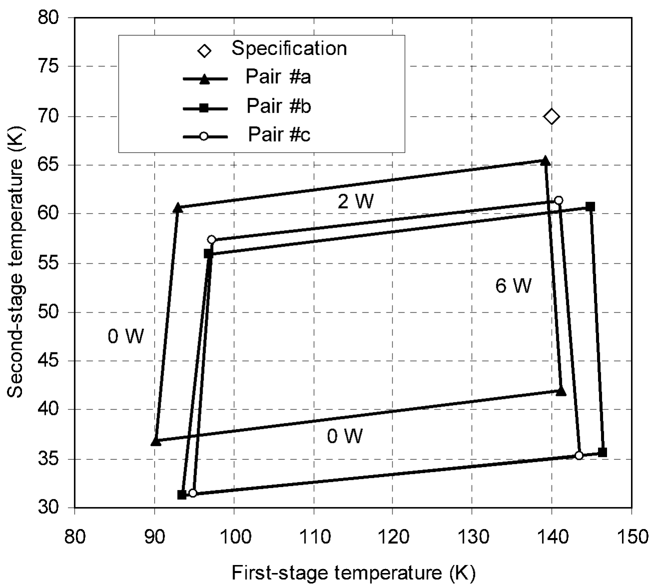


Figure 4. Cooling map for different inertance pairs; 120 W PV, 57.5 Hz, 30 bars, 285 K.

From Figure 4, It can be seen that it is possible to shift cooling power from one stage to the other by changing the values of the inertances. By a simple tuning of the inertances, the cold finger can be slightly adapted to different mission requirements.

One of the results presented (inertance pair #a) is within the specifications, but this is not necessarily the best in terms of thermodynamic efficiency. It is quite difficult to compare different measurements when cooling power is shifted from one stage to the other. Since it is more difficult to produce cooling power at 70 K than at 140 K, we propose to define a new parameter to ease the comparison. This parameter is a weighted average obtained by multiplying the cooling power of each stage by the Carnot efficiency at that stage's temperature. Thus,

$$Weighted\ average = 6.\frac{(Thot - T1)}{T1} + 2.\frac{(Thot - T2)}{T2} \quad (1)$$

where T1 and T2 are the temperatures of the first and second stage, respectively, with 6W and 2W applied, and *Thot* is the temperature of the warm flange (285 K).

In Figure 5, the points giving the same weighted average are plotted as lines labeled “isoefficiency.” With this criterion, inertance pair # c is the better inertance pair. This inertance

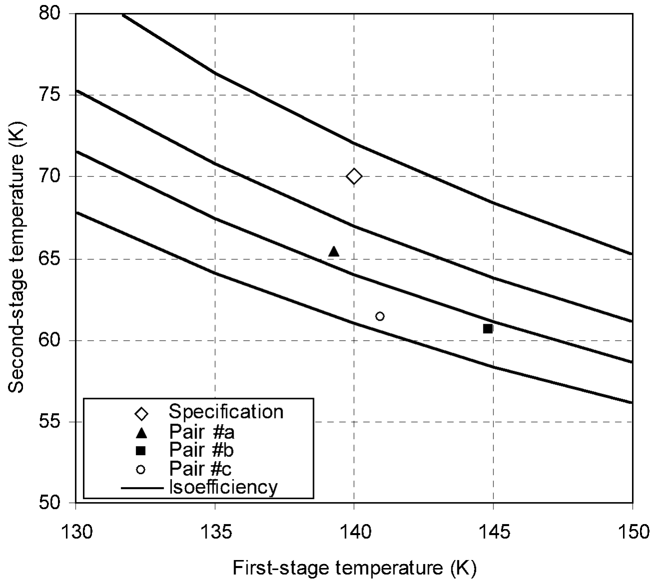


Figure 5. Comparison of pulse tube performance against efficiency.

pair gives a cooling power of 2 W at 61.5 K and 6 W at 141 K with 136 W of electrical power injected to the compressor.

Parasitic Losses

The parasitic heat losses have been estimated by a warm-up method. This method consists of measuring the time for the cold ends to warm up from a given temperature to another one (for example from 65 K to 75 K for the second stage) when the cooler is turned off. This warm-up time is measured with and without a load. Comparison of warm-up times allows one to estimate the parasitic loads.

Due to the large enthalpy of the first stage (large heat exchanger + thermal shielding), it is possible to warm up the second stage with only a small variation of the first-stage temperature. For estimation of the first-stage parasitic losses, the contribution of the second stage is low, and modifications of the temperature of the second stage during first stage warm-up is not critical. The parasitic losses are 150 mW at 70 K/285 K on the second stage, and 1.57 W at 140 K/285 K on the first stage. These values can be reduced by the use of titanium alloy instead of stainless steel for the thin tubes. For the first stage, the large radiation contribution could be reduced for the EM version of the cooler by building a more compact design, thus reducing the surface area of the intermediate heat exchanger and of the thermal shielding.

Effect of PV Power

The change in performance as a function of applied PV power was also examined. For different PV powers ranging from 40 W to 160 W, the temperatures of the two stages were recorded both with loads (6W on the first stage + 2W on the second stage), and without loads. The pair of inertances was chosen for 120 W PV and was kept constant for all the PV-power tests. If we make the assumption that the two stages are relatively independent of one another, it is possible to estimate the cooling power on the first stage and second stage for a given set of temperatures such as 140 K and 70 K. This estimation is reported in Figure 6. Note that this estimation is quite rough because the performance of the two stages is not fully independent. These data are represented only to give an idea of the potential capability of the cold finger for different PV powers.

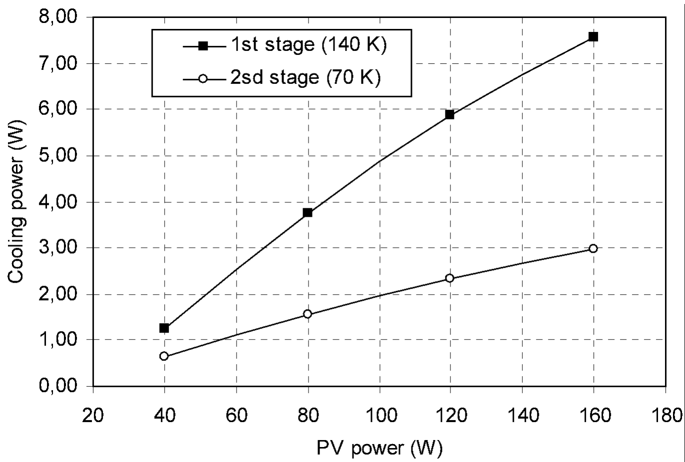


Figure 6. Effect of PV power on cooling power of the two-stage pulse tube; 57.5Hz, 30 bars, 285K.

Effect of Rejection Temperature

The effect of rejection temperature has also been investigated. The water mass flow rate was decreased in the warm flange water cooling circuit so as to increase the warm temperature. The temperatures of the first and the second stages were measured with applied loads of 6 W on the first stage, and 2 W on the second stage. The results are presented in the Figure 7.

As expected, the second stage is less sensitive (0.26 K/K) than the first stage (0.47 K/K) to modification of the rejection temperature. Nevertheless, the second stage sensitivity remains quite high compared to that of a single-stage pulse tube cold finger. For example, the LPTC cooler has a sensitivity of 0.21 K/K at 50 K. At least two reasons can explain this result: the first one comes from the present design where the second stage shows a high sensitivity to the first-stage temperature as shown in Figure 4. When 6 W is applied on the first stage, leading to an increase of first-stage temperature, the second-stage temperature increases as well.

The second reason is the fact that the first stage is very sensitive to warm temperature variations. Once again, this is due to the present design, but this is also due to the use of stainless steel tubes that lead to important conductive losses. It should be possible to change the design in order to make the second stage pulse tube less dependent of the first one; for example, by increasing the second-stage regenerator length. An EM model using titanium alloy for the tubes should give better results.

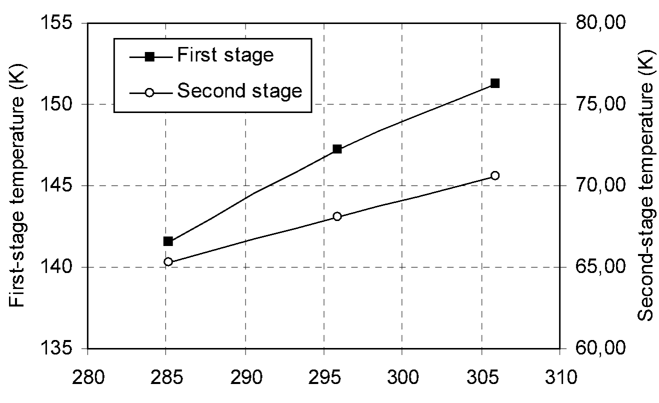


Figure 7. Effect of rejection temperature on first- and second-stage temperatures for applied loads of 6W and 2W; 30 bars, 57.5 Hz, 120 W PV.

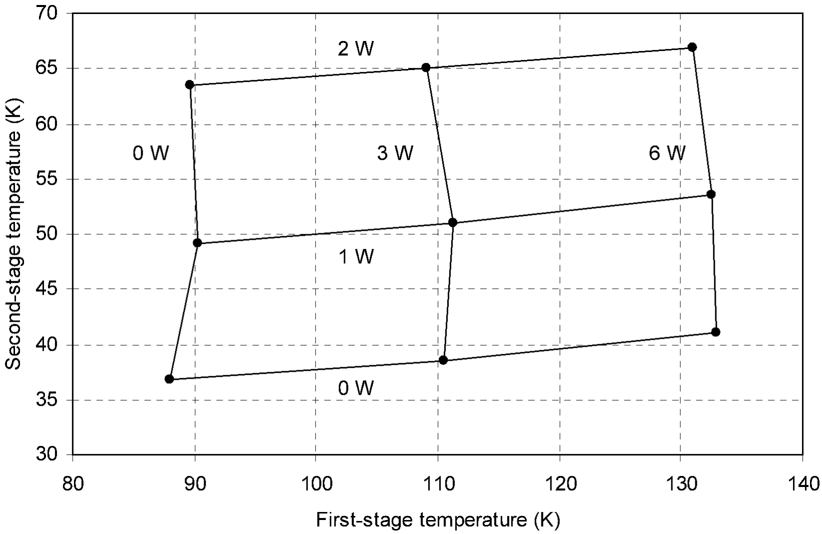


Figure 8. Cooling load map; 30 bars, 57.5 Hz, 285 K, 120 W PV.

Last Results

Finally, a new configuration with a larger tube on the first stage has been developed. Only two pairs of inertances have been tested up to now. The best results obtained are presented in Figure 8.

This new configuration allows the performance of the first stage to be increased with only a small degradation of the second-stage performance. Cooling powers of 2 W at 67 K and 6 W at 131 K have been achieved with 136 W of electrical power input to the compressor. Measurements with half the nominal cooling power have been performed on this configuration. Cooling powers of 1 W at 51 K, and 3 W at 111 K, have been achieved with 138 W of electrical input power.

PERSPECTIVE

Other configurations will be tested in order to increase the overall efficiency of the cold finger and/or to change the cooling power partitioning between the two stages. This could allow the cold finger to be tailored somewhat for specific mission requirements. One of the configurations will be selected to carry out an engineering model (EM) conceptual design.

CONCLUSION

A two-stage pulse tube cold finger prototype has been designed, built and tested. This cold finger is foreseen to be used in Earth-observation missions and could be coupled with an existing LPTC compressor that is under qualification. With this compressor, cooling powers of 2 W at 67 K and 6 W at 131 K have been achieved simultaneously, while applying 136 W of electrical power.

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