Experimental Results of 20 K Pulse Tube Cold Fingers for Space Applications

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ABSTRACT

Pulse tube cryocoolers are an appropriate technology for providing cooling powers of several hundred milliwatts at 20 K for space applications. In the framework of an ESA contract (ESA/ESTEC N°20497/0/NL/PA – 20/50 K Pulse Tube Cooler), we developed, manufactured and tested single and two-stage cold fingers in this temperature range. A single-stage pulse tube cryocooler with a heat interceptor around 80 K has been designed. A cooling power higher than 300 mW at 20 Kelvin has been achieved. In parallel, we designed and tested a two-stage pulse tube cryocooler with second-stage cooling at 30 K and a first-stage temperature of 120 K. Compression power for these pulse tubes ranged from 100 to 120 W PV. Experimental results on these two kinds of cold fingers are presented. Comparison of these different designs and of their measured performance is discussed.

INTRODUCTION

Several future space missions will require cooling power below 20 K. Requirements for such temperature levels include precooling for Joule-Thomson refrigerators and focal plane or electronic device cooling. Pulse tube type cryocoolers, with no cold moving parts, are an attractive technology that fulfills the constraints imposed on space cryocoolers in term of reliability, lifetime, and self-induced vibration.

Our team has wide expertise in the pulse tube development field and has demonstrated several single-stage pulse tube coolers for 50-80 K experiments. As an example, the MPTC[1] and LPTC[2] coolers have been developed in partnership between CEA/SBT, Air Liquide, and Thales Cryogenics with the support of ESA. CEA/SBT has also developed low frequency two-stage pulse tube cryocoolers.[3]

As the operating temperature decreases, the use of multistage cold fingers offers a higher efficiency due to the intermediate stage providing an important reduction of the losses on the colder stage. The project described herein deals principally with two-stage pulse tube coolers. For such a
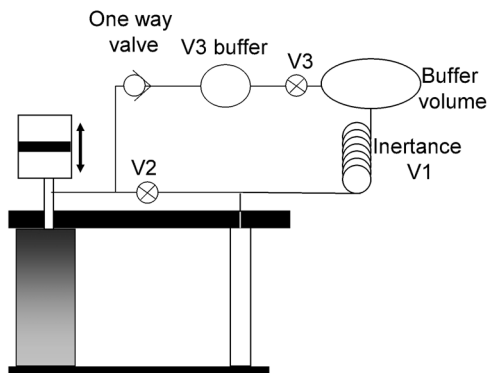
Figure 1. Detailed description of the inertance, V2 / V3 phase shifter.
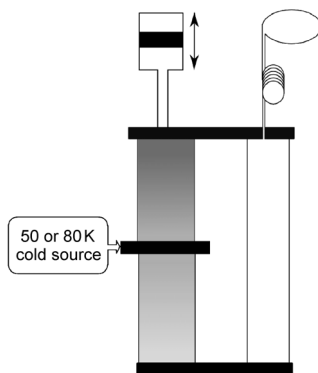
Figure 2. Pulse tube with intercept.

configuration, two designs have been considered: a pulse tube with heat intercept[4] (conduction coupling), and a standard two-stage cryocooler (gas coupling). Both these configurations are detailed below. For these laboratory prototypes, the phase shifter uses a set of valves and a buffer volume.

COMPRESSOR AND INPUT POWER

One of the goals of this work was to design a pulse tube optimized for the LPTC compressor.[2] This compressor has been developed in the framework of a previous ESA contract(N°18433/04/NL/AR) dedicated to the design and test of a 2.3 W at 50 K pulse tube cooler. This implies an operating frequency of 57.5 Hz, a PV power of 120 W and a swept volume of 7.54 cubic centimeters. In its nominal design, the mean pressure is 30 bars. The pressure could be reduced as long as the swept volume used is not higher than the nominal one.

In this paper, PV power is defined as the electrical power measured minus the Joule losses. This PV power is therefore overestimated (or pessimistic in regards to pulse tube performance) because all other compressor losses are neglected, but that gives us an easily measurable quantity.

For our single-stage pulse tube experiment, a commercial Thales type 8220 moving coil compressor was used. For the two-stage pulse tube, a commercial Thales type 97xx maxi compressor[9] was acquired. This compressor has a maximum swept volume of 22 cc and a maximum electrical power of more than 600 W. This tool allowed more thorough experiments, with a constant PV work of 120 W thorough a wide range of driving frequencies.

PHASE CONTROL

For both designs, the phase between pressure and mass flow is obtained thanks to the use of inertances and also by using a bypass (V2) configuration. In parallel with the cold finger, a third valve that we called V3 is used in conjunction with a one-way valve to control the DC flow that can occur in such a configuration (Figure 1). This setup has been described previously[5] without inertances. It allows an independent setting of the flow between the inlet of the regenerator and the output of the tube with the V2, and then to control the DC flow thanks to the use of the valve V3.

PULSE TUBE WITH INTERCEPT CONFIGURATION

The configuration "pulse tube with intercept" has been described in a previous paper[6] and is schematically shown in Figure 2. The regenerator is divided into two parts separated by a heat exchanger. This heat exchanger (interceptor) is thermally connected to a cold source at a temperature around 80 Kelvin. This setup is especially advantageous when a cold source is available, as is the case for a satellite with efficient passive radiation cooling, such as with a V-groove radiator. One way to explain the advantage of this configuration is to look at the temperature gradient in the regen-
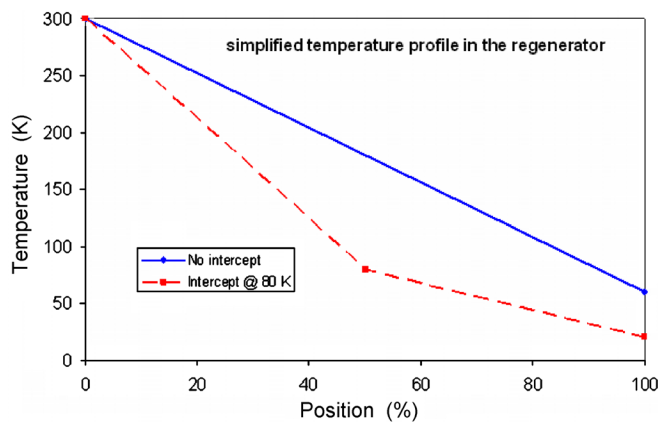
Figure 3. Simplified temperature gradient in the regenerator.

erator as plotted in Figure 3. The temperature gradient in the regenerator's cold part is reduced, and therefore the thermal losses in the regenerator are reduced. Given an appropriate setting of the pulse tube, the cooling power available for a given input power is increased. On this subject, an extensive study has been made of the MPTC pulse tube with heat intercept.[7]

In space, and especially for L2 missions, passive cooling can be used to obtain precooling at temperatures varying from 50 K to 120 K. In our laboratory, the cooling power is obtained by the use of a G-M cooler[6] as is represented in Figure 4. The cooling power is estimated from the measurements of the temperature gradient in a calibrated copper braid. The cooling power available when using an equivalent of 2 m[2] radiation panel minus 0.5 W used for compensating various losses is plotted in Figure 5. For this study, our goal was to work with a cooling power compatible with these values. It is important to notice that for radiation cooling, the available cooling power grows quickly (power of 4) with temperature (3.7 W at 80 K, 6.2 W at 90 K).

Several configurations have been designed. The results of the best three are presented here in Table 1. The modification includes variations of regenerator and tube dimensions.

Table 1. Comparison of the different configuration of pulse tube with intercept studied.

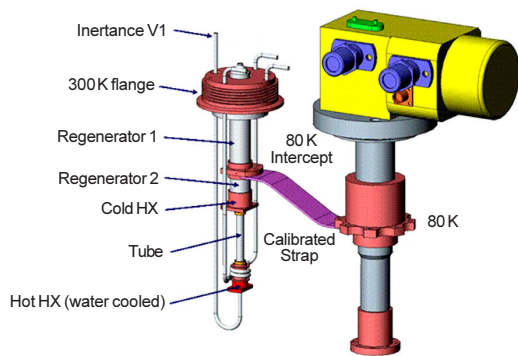| Configuration	Characteristic
Configuration # 1	Base configuration
Configuration #2	Longer Cold Regenerator
Configuration #3	Shorter Tube

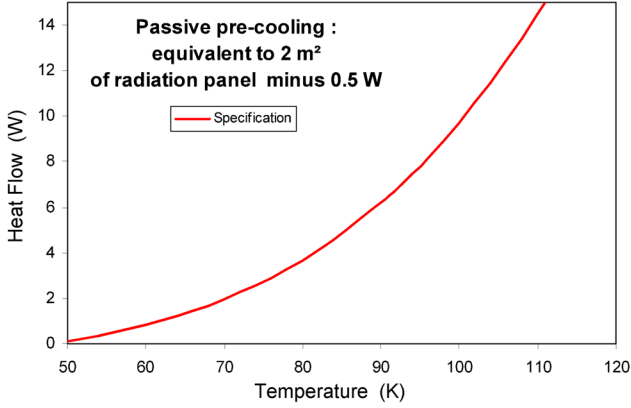**Figure 4.** Pulse tube with 80 K intercept supplied by GM cooler.

Figure 5. Cooling power available as function of intercept temperature.
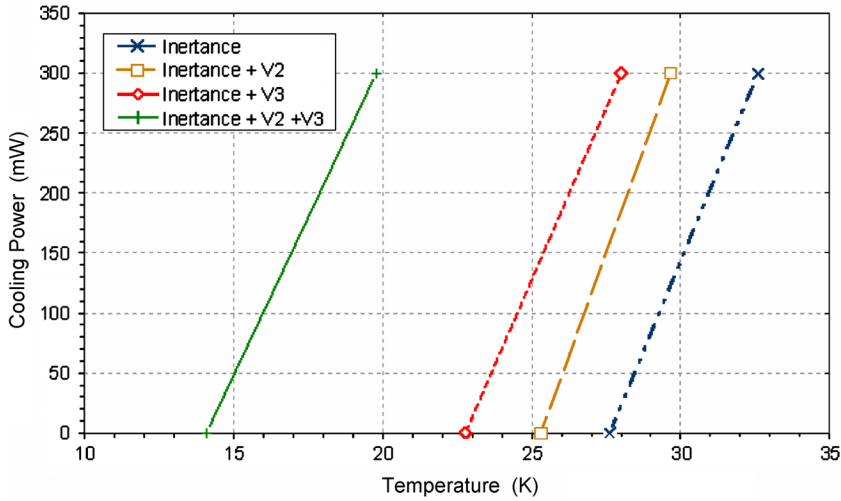

Figure 6. Results with different kinds of phase shifter.

## THERMAL PERFORMANCE MEASUREMENTS ON A PULSE TUBE WITH HEAT INTERCEPTOR PRECOOLER

For these experiments, the V2 and V3 phase shifter were used. The gain due to these phase shifters is significant as can be seen in Figure 6. One can see the gain for an equivalent configuration is on the order of 5 K for the addition of V3 and 15 K with both V2 and V3. In another case, with V2 closed, we measured a gain of 8 K with the addition of V3 (Figure 7). There are three important conclusions from these experiments:

- It is confirmed[10] that a DC flow is actually necessary to improve the performance, and the addition of V3 gives way to improved performance even if no V2 is used.
- The second one is that the phase shift due to the inertances is probably not sufficient to perfectly tune the pulse tube.
- The value of the DC flow (see Figure 7) has a large impact on the intercept cooling power.

On different prototypes, cooling powers exceeding our original objectives have been measured. In Figure 8, one can see that an ultimate temperature of 12.6 K has been measured. Also, a cooling power above 100 mW at 15 K has been measured. For configuration #1, a cooling power of 300 mW at 19.6 K has been achieved with 6 W intercepted at 80 K.
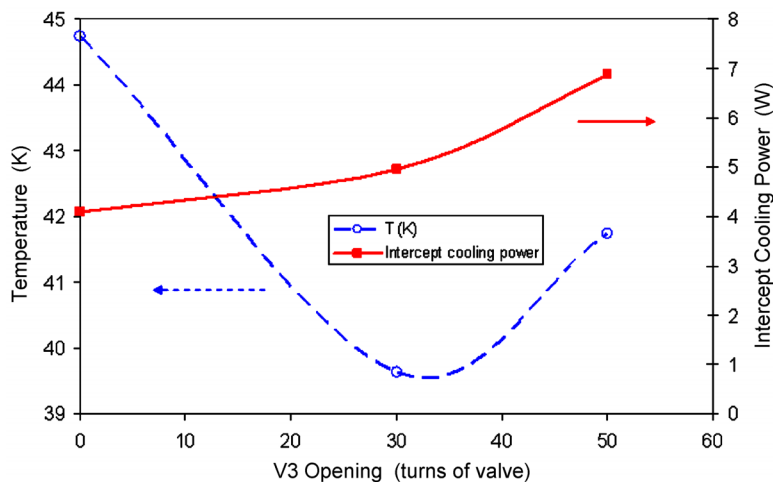
Figure 7. Variation of required heat intercept cooling power and cold tip temperature as function of V3 opening. Mean pressure of 20 bars, frequency of 41 Hz, cooling power of 300 mW and intercept temperature of 80 K. V2 is closed.
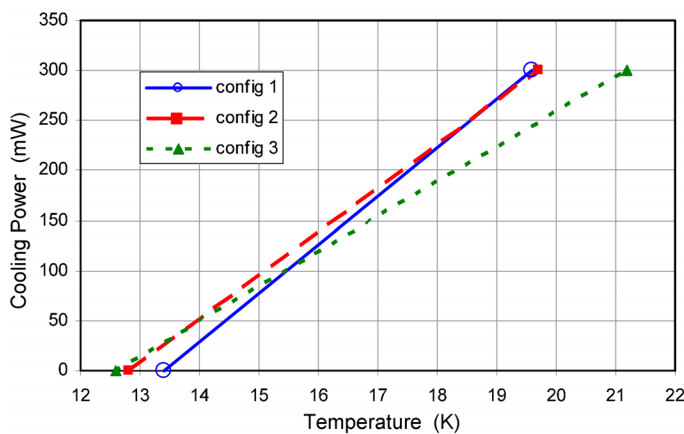

Figure 8. Comparison of the thermal performances of several configurations pulse tube studied.

TWO-STAGE PULSE TUBE ARCHITECTURE

Our two-stage pulse tube cooler is based on the same design as typical two-stage low frequency pulse tube[8,3] coolers and is represented in Figure 9. The two regenerators are in line, and the tubes are connected between the cold exchangers of each stage and the room-temperature base plate. V2 and V3 are used for the second stage only.

A prototype pictured in Figure 10 has been manufactured and thermally tested. This prototype is modular, meaning it is possible to change easily the geometry of each tube and the regenerator of the second stage. The cold end of the second regenerator can easily be removed thanks to an indium-sealed flange. This will ease the study of different regenerator fillings. One of the complexities in terms of design for this U-shape version is the connecting tubes between each regenerator and the pulsation tubes. Assembly constraints impose a certain distance between these tubes, which causes dead volume and pressure losses. An engineering model of this two-stage pulse tube cooler would include at least some coaxial features.
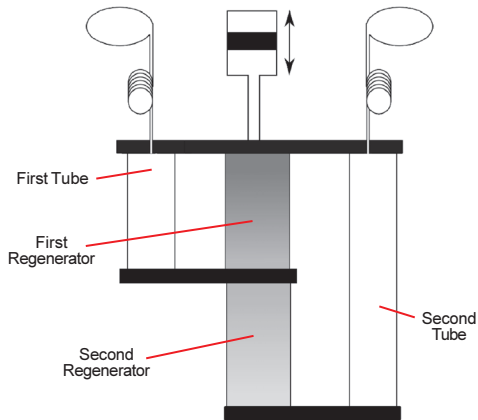
Figure 9. Sketch of our two-stage pulse tube cooler. The positions of V2 and V3 are not represented in the drawing.

Figure 10. Picture of our two-stage pulse tube.
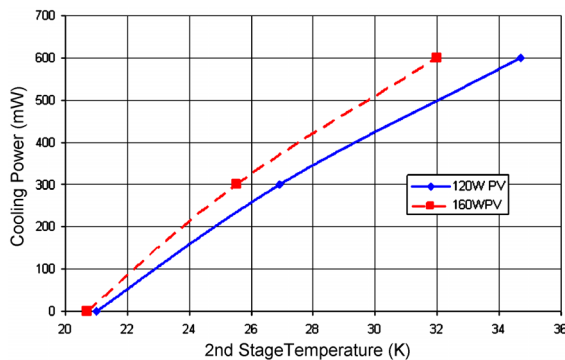
THERMAL PERFORMANCE OF TWO-STAGE PULSE TUBE

Our two-stage pulse tube has been tested with different cooling powers and input PV powers. V2 and V3 have been used on the second stage only. The cooling power measured for PV powers of 120 or 160 W is plotted Figure 11. A cooling power of 300 mW at 26.9 K has been measured with 120 W of PV power.

Experiments have been carried out at various filling pressures, and the results are presented in Figure 12. Optimization has been done at 20 bars and the inertances have not been changed for each filling pressure.

A higher filling pressure would probably allow an increase of the performance for high cooling power, especially on the first stage.

CONCLUSION

Several pulse tube cryocooler prototypes have been designed and thermally tested. A two-stage pulse tube cooler providing in excess of 300 mW at 27 K with a first stage below 120 K has been demonstrated. In parallel, a pulse tube taking advantage of passive cooling at 80 K has been tested with a cooling power of more than 300 mW at 20 K, or 100 mW at 15 K. From these encouraging thermal performance measurements, an Engineering Model is being designed to fit ESA engineering model requirements.

Figure 11. Second-stage temperature for PV powers of 120 W and 160 W. First-stage temperature ranged from 115 to 120 K and is not represented.
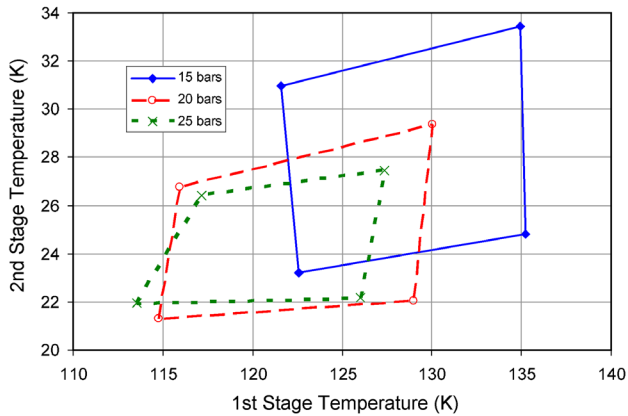
Figure 12. Thermal performance of the two-stage pulse tube for 3 different fill pressures. Results are presented for 0 and 1 W on the first stage, and 0 and 300 mW applied to the second stage. All are with 120 W PV input power and a frequency of 55 Hz.

ACKNOWLEDGMENT

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