

# Prototyping a Large Capacity High Frequency Pulse Tube Cryocooler

**J. Tanchon<sup>1</sup>, T. Trollier<sup>1</sup>, A. Ravex<sup>1</sup>, and E. Ercolani<sup>2</sup>**

<sup>1</sup>Air Liquide Advanced Technology Division, AL/DTA  
Sassenage, France

<sup>2</sup>CEA/DSM/DRFMC/Service des Basses Températures  
Grenoble, France

## ABSTRACT

A Very Large Heat Lift Pulse Tube Cooler (VLPTC) is currently under development in partnership between AL/DTA and CEA/SBT. This pulse tube cold head prototype is based on an in-line configuration to ease the prototyping. It makes use of an inertance tube and a buffer volume as a phase shifter. The pulse tube cold head is driven by an 8 kW flexure bearing linear compressor. The performance is presented and discussed for various configurations and input powers.

## INTRODUCTION

Air Liquide DTA is developing a high capacity pulse tube cooler to offer a solution to the cryogenics needs of High Temperature Superconductor (HTS) devices. Today, Gifford McMahon (G-M) coolers are most commonly used for the industrial and laboratory applications of HTS devices. The high vibration level and the maintainability constraints do not make these coolers the best solution for high cooling power systems. The coming industrial exploitation of HTS devices, relies on maintenance-free cryocooler integration with a higher efficiency and reliability than the one proposed by the current G-M solution.

## DESIGN AND MANUFACTURING

This pulse tube cryocooler uses a 8 kW flexure bearing pressure wave generator. The cold head is an in-line configuration for the prototyping and has been modeled and designed with a requirement for 280 W @ 65 K with 8 kW of input power (see Figure 1). The Table 1 presents the critical design parameters.

The technology used for the heat exchangers of the prototype is based on slots heat exchangers. This technology is the best compromise between dead volume, pressure drop and heat exchange surface.

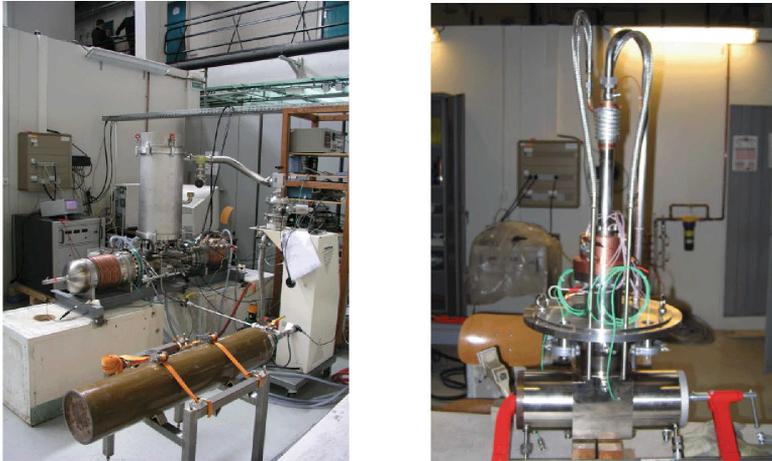
## PRELIMINARY TESTS AND OPTIMIZATION

### Preliminary Tests

The first tests carried out on this prototype were encouraging. For the first cool down, a no-load temperature of 41 K was reached and a cooling power of 100 W @ 77 K was achieved for

**Table 1.** Pulse Tube Design Parameters

	Output from the model	
Input power	5.5	kW
Compression work	4.7	kW
Pressure wave	4.42	Bar
Swept volume	235	cc
$T_{\text{cold}}$	60	K
Cooling power	254	W
No-load temperature	29,4	K

**Figure 1.** VLPTC Prototype and cold head overviews

4400 W of compressor work (PV work). The goal of the first tests was to validate the critical points of design such as the aftercooler, the cold and hot exchangers, as well as the resonance of the oscillator coupled with the cold head.<sup>1</sup> For the aftercooler, the temperatures and real time pressures measurements enabled us to validate the pressure drops and the thermal efficiency of the heat exchangers.

### Effect of the Inertance

The optimization of the inertance, contrary to the low capacity cryocoolers, is not sufficient to find the best configuration of the cooler. For the VLPTC, we tested a batch of inertances by varying the diameter and the length. These tests did not produce an optimal inertance because the same optimum on cooling power had been found for the various diameters tested (Fig. 2). The first results are encouraging, but are not sufficient.

### Effect of the Regenerator Length

The first configuration tested resulted in an interesting no-load temperature (41 K) with a lower cooling power than expected. To increase the cooling power at 65 K, we have tested shorter regenerators. All regenerators are made of homogeneous stainless steel meshes with no grading. The experimental results produced a 60 mm optimal length for this regenerator diameter (Fig. 3).

Tests performed with the longer regenerators (80 mm and 120 mm) showed difficulties to achieve the targeted PV work. The maximum swept volume of the compressor was reached before achieving sufficient pressure swing at the inlet of the cold finger. Beside the fact that these two regenerators have too large a volume to be well coupled with this compressor. The regenerators are potential candidates to reach lower limit temperature.

Additional tests have been also performed with a larger regenerator diameter. The objective was to reduce the pressure drop while keeping the same volume found on the best regenerator

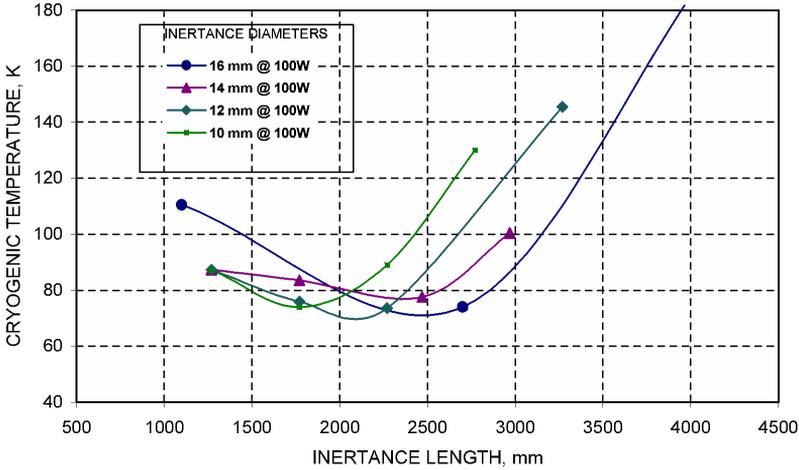


Figure 2. Effect of inertance length on temperature with 100 W heat load

previously experimented. Because the global heat capacity of the regenerator and the mass flow are conserved, we should have measured an increase in the slope of the load curve without degrading the no-load temperature. However, the experimental results do not produce an easy conclusion. The coupling between the compressor and the cold finger is not the same as the one used during the previous tests. By increasing the diameter of the regenerator and by keeping the same pulse tube diameter, we have increased the flow resistance in the cold heat exchanger location. This flow resistance is due to the ratio between the diameter of the pulse tube and the regenerator. This results in a drastic decrease of the maximum PV work injected in the pulse tube and a reduction in the cooling power.

### DISTRIBUTION FLOW ANALYSIS AND TESTS OF THE PULSE TUBE CRYOCOOLER

#### Measurements of the Temperature Profile around Two Regenerator Diameters

The first tests performed on the prototype indicate that some problems occur in the flow distribution and disturb the cooling production. In order to verify and to quantify this potential problem, we decided to measure the azimuthal temperature distribution at two regenerator locations. Four temperature sensors were placed on the outer surface simultaneously at the first and the last third of

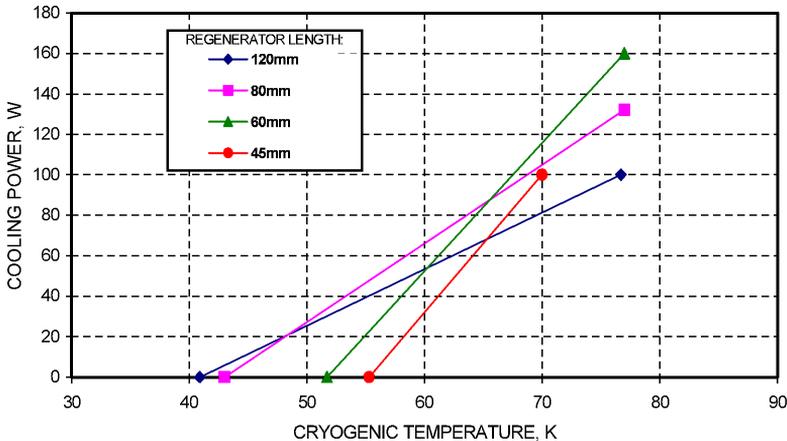


Figure 3. Effect of the regenerator length on cooling power with 4,4 kW

the regenerator. Again, the results were not conclusive. We noticed no significant improvement contrary to Thummes and al.<sup>2</sup> who measured a thermal gradient of 120 K on their large pulse tube cooler. The temperature difference around the regenerator diameter can induce recirculating flows in the radial direction and decrease the cooling power. For the configuration tested, the thermal gradients measured are close to 30 K with no-load and 23 K with 100 W of cooling power. These thermal gradients are far from those measured by Thummes, et al.<sup>2</sup>

### Effect of the Regenerator Materials

The solution proposed and tested by Thummes et al.<sup>2</sup>, was to increase the radial conductivity of the regenerator. An increase of this conductivity can reduce the gas temperature difference around the regenerator and the convective effect. We implemented this solution in our regenerator (80 mm length) by replacing the stainless steel meshes with brass meshes of the same geometrical parameters. With this configuration, the results are completely different from those obtained by Thummes et al. in the sense that the thermal gradients were effectively reduced from 23 K to a few K. We did not measure a significant difference in the cooling power between these two regenerators (Fig. 4).

Thus, we expect that the major problem is not coming from convective effect in the regenerator because the phase shift in the cold head is not varying significantly due to a limited effect of the inertance and because we have a good PV work at the inlet of the cold finger. We attribute the problem to a flow perturbation in our system.

### Simulation of the Flow in the Regenerator

A 3D model of the cold finger and dynamics calculations has been developed with a commercial software to visualize the oscillating flow that occurs in the cold finger. Simulations with various regenerators' thermal conductivities have been performed and did not show any critical problems on the flow. The important parameter that we have neglected before this analysis is the cold flow straightener thickness. A simulation with and without the flow straightener revealed a big difference in the flow in the regenerator. With a cold flow straightener thickness of 1.6 mm (left side of Figure 5), simulations show recirculation in the regenerator during the compression phase reducing the mass flow in the pulse tube. For the same configuration but without cold flow straightener (right side of Figure 5), the recirculation is suppressed and the mass flow in the pulse tube increased. This confirms that our problem is due to a recirculating flow coming from the cold flow straightener (and not from the regenerator).

### Effect of the Flow Straightener Thickness

To validate this analysis and to increase the cooling performances, we have tested different cold flow straighteners by varying the thickness of the stack. We tested cold flow straightener

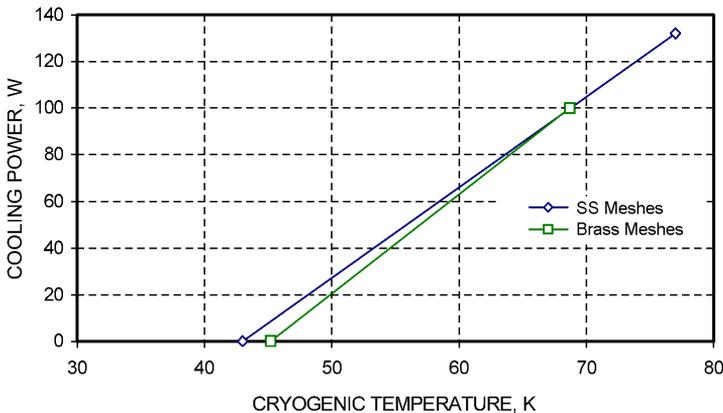


Figure 4. Effect of the regenerator material on the cooling power with 4,4 kW

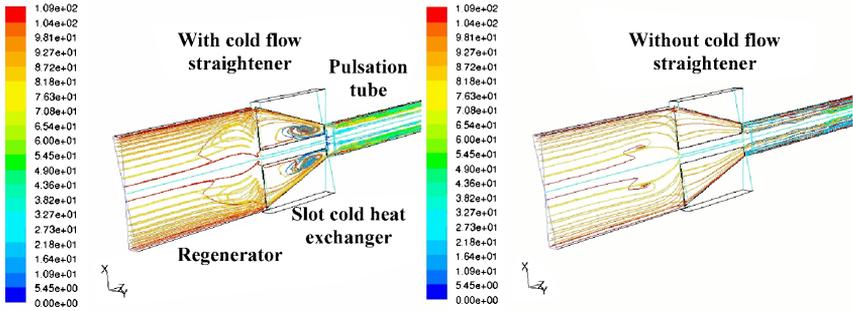


Figure 5. Flow distribution in the cold head (compression phase)

thickness varying from 1.6 mm to 0.5 mm for the optimum regenerator configuration (60 mm, refer to Figure 3). Measurements confirmed our analysis. The cooling power, for the same configuration, increased from 115 W @ 65 K to 210 W @ 65 K with 6 kW compression work (Fig. 6).

The same work has been performed with hot the flow straightener. The thickness of the stack has been also decreased to 0.4 mm but without significant difference on the cooling power than the one achieved with 1 mm. Notice also that no flow straightener has drastically decreased the performance.

**Conclusion on the Optimization**

The cooling power after optimization of the flow straightener thickness (0.5 mm) increases from 115 W to 210 W @ 65K. Figure 7 shows the capacity curve of the VLPTC for two different compression works optimized for this configuration. We observe on the load curve that the no-load temperature increases with the PV work resulting in a lower efficiency for 6 kW than for 4 kW.

**COMPARISON OF THE VLPTC WITH COMMERCIAL COOLERS**

The objective of this development was to propose an alternative solution to Gifford-McMahon (G-M) cryocoolers for applications requiring no maintenance and high reliability. There are not a lot of manufacturers of large heat lift capacity coolers. To evaluate the interest of this prototype in term of cooling capacity, it’s necessary to compare these performances against G-M coolers commonly used and pulse tube coolers under development. For that purpose, the load curves have been plotted on the Figure 8 and the COP (cooling power/electrical input power) calculated at 65 K have been presented in Table 2.

Currently, the COP of a mature G-M cooler is higher than those of pulse tube coolers. At 65 K, the COP of our VLPTC presented herein is 3.2 % for 5.5 kW input power (4 kW PV) and 2.8 % for

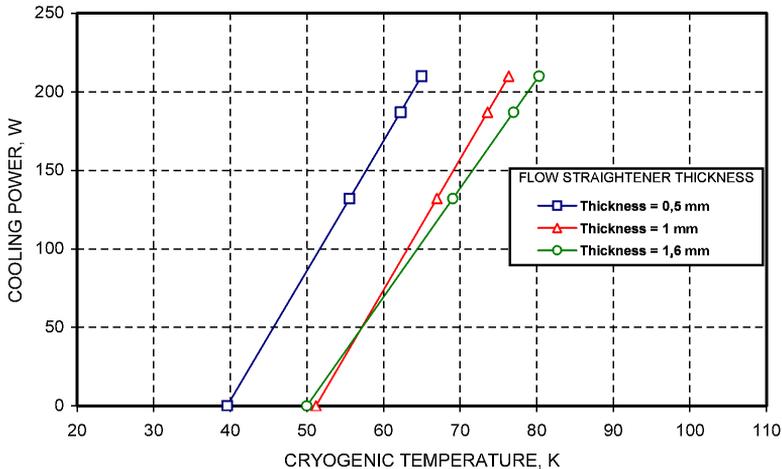
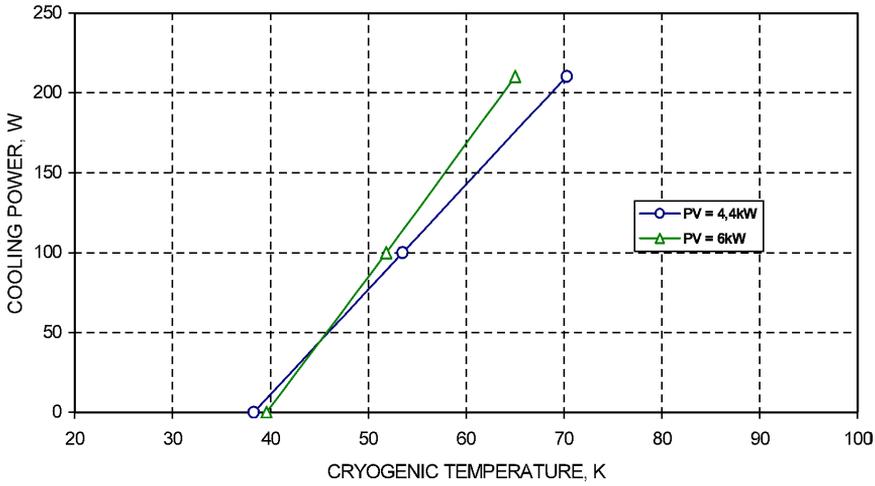


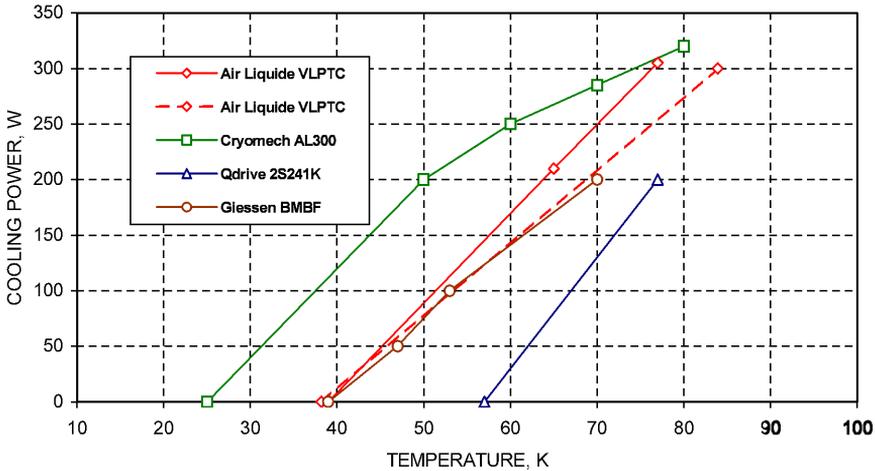
Figure 6. Effect of the flow straightener thickness on the cooling power with 6 kW

**Table 2.** Available coolers for 65 K

Manufacturer	Model	Type	Cooling power @ 65K	Electrical input power	COP @ 65K
<b>Cryomech</b>					
	AL330	GM cooler	220 W	7,5 kW	2,9%
	AL300	GM cooler	270 W	7,5 kW	3,6%
	AL600	GM cooler	500 W	14 kW	3,6%
<b>Qdrive/Praxair</b>					
	2S241K	PT cooler	80 W	4,2 kW	1,9%
<b>Giessen University</b>					
	Prototype	PT cooler	170 W	7,8 kW	2,2%
<b>Air Liquide</b>					
	VLPTC	PT cooler	210 W	7,5 kW	2,8%
			175 W	5,5 kW	3,2%



**Figure 7.** Load curve of the VLPTC for two different PV work



**Figure 8.** Load curve for the different cryocoolers

7.5 kW (6 k PV). This result is very promising for the next step in the development and shows a real potential for this technology to be an alternative to G-M coolers.

## CONCLUSION

The Very Large Pulse Tube Cooler performance is very encouraging. Some tests on the flow straightener structures will be performed in the coming months with an objective of cooling power of 280 W @ 65 K for 6 kW PV work. The pulsation tube volume could impact the performances. However, during the present work, we did not modify and optimize it due to experimental constraints. This step will be investigated.

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