Impact of the cold regenerator mesh geometry on low temperature pulse tube cold finger performance

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Abstract. Future astrophysics missions such as SPICA, Athena or LiteBird will need a cooling below 1 K (until 50 mK) to achieve the detectors’ required sensibility. To address such requirements, cooling chains are built coupling several technologies using intermediate temperature cooling, explaining why a high cooling power at 15 K is essential. The CEA-DSBT designed, for lab test purpose, a Pulse Tube cooler system consisting of a heat intercepted single-stage cold finger which is pre-cooled by a Gifford McMahon cryocooler. The cold part of the PT, in particular the regenerator, is critical to the PT cooler performance. Keeping the regenerator material standard (stainless steel mesh), we study here the influence of the cold regenerator mesh geometry on the operation of the cold finger. The wire thickness is varied, which modifies the porosity, the dead volume and the heat surface exchange of the regenerator. Experimental results on different mesh designs are presented here and analysed, showing a significant influence of the mesh geometry on the performance.

1. Introduction
The need for very low temperature (< 100 mK) is becoming predominant for some of the most sensitive future astrophysical space missions. To reach such a low temperature level and keep it for a long duration, a cryogenic chain architecture including a sub-K cooler and several Joule-Thompson coolers and precoolers shall be used. In order to optimize the Joule-Thompson operations, a precooling is needed preferably at 15 K or lower.

Our lab in CEA-DSBT has developed for more than 10 years pulse tubes cryocooler reaching such low temperatures, in collaboration with CNES and ESA which partially funded our development. We focus on the development of novel regenerator materials for low temperature [1-3] and on the architecture of multi-stage pulse tube cooler [4, 5].

Based on our results and on common developments with Air Liquide Advanced Technologies and Thales Cryogenics B.V., an engineering model of a heat intercepted 15 K pulse tube cooler has been designed. Its architecture is a single-stage 15 K pulse tube cooler precooled at 80 K – 120 K by a single stage Large Pulse Tube Cooler developed for earth observation [6]. This cooler is now in the baseline on ATHENA/X-IFU instrument cooling chain [7] to cool thermal shields and to precool 2K and 4K JT coolers from JAXA. For lab test purpose, a similar pulse tube cooler has been designed, which operating principle is presented in Figure 1.
This paper presents a study of the cold regenerator, composed of stainless steel mesh. As the cold part of the pulse tube cooler is critical to the performance, we intend to measure the impact of the mesh geometry on the lowest temperature and available cooling power of the pulse tube cold finger. Through the variation of the porosity, dead volume and heat surface exchange, a significant impact of the mesh thickness is highlighted.

![Compressors (input power and active phase shift)](image)

**Figure 1.** Single 15 K PT, precooled at intercept.

2. **Experimental Setup**

The pulse tube cooler is filled with Helium at 20 bars. A main compressor provides an input PV power of 100 W at variable operating frequencies between 35 and 45 Hz, and the output of the cold finger is linked to a second compressor acting as an active phase shift setup to precisely control the phase between pressure and mass flow.

The hot and the cold regenerators are composed of stainless steel mesh, providing good thermal exchange properties with the oscillating gas. Most of the heat loss of the cold finger coming from the ambient temperature is removed at the intercept -which separates the hot regenerator and the cold regenerator- by a commercial Gifford McMahon cryocooler. The thermal regulation of this intercept between 50 and 120 K emulates the real precooling of the single 15 K pulse tube cold finger by a LPTC, as used in the EM model built by Air Liquide [6].

In order to study the impact of the cold regenerator mesh on the pulse tube cooler performance, the thickness of the stainless steel mesh of this regenerator were changed, leading to the geometries presented in Figure 2. The reference configuration has the thickest mesh, used to normalize the other values. The cold half or the full cold regenerator are then filled with thinner mesh, with a number of meshes inversely proportional to their thickness.
3. Results

The performance of the pulse tube are measured at the cold tip. A characterization of the pulse tube can be obtained by plotting the cooling power available at cold tip as a function of the temperature of this tip. For each regenerator geometry, three measurements are made:

1. The lowest temperature achieved, at which zero cooling power is delivered.
2. The cooling power available if the cold tip is at 15 K. To determine it, the cold tip is heated until 15 K and we measure the required power to reach this temperature.
3. The temperature of the cold tip when heating it with 1 W.

In parallel with the performance measurements, a stability study is conducted to estimate their uncertainties. The lowest temperature and the cooling power at 15 K are recorded every day during the test campaign. An example is shown in Figure 3 for the full cold regenerator filled with 0.88 thickness mesh, with a frequency of 41 Hz and an intercept temperature of 80 K. So we consider that the performance is stable within ±3% for the temperature and ±10% for the cooling power.

![Figure 3](image-url)
Measurements have been made for 3 frequencies (36, 41 and 46 Hz) and 3 intercept temperatures (50, 80 and 120 K) for each geometry. We observed an increase of the performance when the frequency is low and when the intercept temperature decreases, as illustrated in Figure 4 for the full cold regenerator filled with 0.88 thickness mesh.

![Figure 4](image_url)

**Figure 4.** Influence of the frequency and the intercept temperature on the performance for the full cold regenerator filled with 0.88 thickness mesh.

The same measurements are made for each configuration, leading to a large amount of data. Here we propose to average all the results obtained in each individual configuration to make the trends clearer. These mean performance curves are shown in Figure 5. The less efficient geometry is the reference one, showing a significant influence of the mesh thickness.

![Figure 5](image_url)

**Figure 5.** Cooling power available at cold tip depending on its temperature.

To estimate more precisely the dependence of the performance on the mesh thickness, a comparison of the geometries for each measurement point (lowest temperature, cooling power at 15 K and temperature at 1 W) is presented in Figure 6. The data are the same as in the Figure 5 but this new point of view allows a better understanding of the differences between the lower part -cold- and the upper part -hot- of the cold regenerator.
The behavior of the cold regenerator varies, according to its filling rate with thinner mesh. Considering the lowest half part of the cold regenerator, an optimal thickness shows up depending on the temperature: at low temperature -around 12 K-, the performance increases when the thickness decreases from 1 to 0.82. An optimum could appear at a lower thickness than 0.82 but its determination would require some additional measurements. At 15 K, as the performance for thicknesses of 0.88 and 0.82 are similar and better than the reference, an optimum about 0.85 appears. Up to 25 K, the trend is more pronounced and the best thickness increases to 0.9.

From our measurement, for the upper part of the cold generator the performance of the pulse tube is always better in the thinnest mesh case, despite the different trends for the lowest part of the cold regenerator. It means that it is better to have mesh whose thickness is less than 0.82 in the upper part of the cold regenerator. An optimum thickness should exist but some additional experiments would be required to obtain a precise value.

4. Analysis
To explain the observed trends it is crucial to note that, as the regenerator height is constant, the mesh thickness decreasing induces a higher number of meshes to fill the regenerator. This leads to some changes in the matrix properties, inducing some positive or negative impact on the final performance.

4.1. Positive effects quantification
A direct impact is an increase of the thermal capacity of the matrix when increasing the mesh quantity, in the proportions presented in Table 1. These values comes from an experimental counting of the mesh number inside each configuration. The exchange surface between gas and stainless steel matrix proportion are also enhanced when the mesh are more numerous, in the same way as the thermal capacity as estimated in Table 1. That should improve the performance because it improves the heat transfer.
**Table 1.** Thermal capacity and exchange surface variation, compared with the reference geometry.

|                      | Half cold regenerator | Full cold regenerator |
|----------------------|-----------------------|-----------------------|
| **Thickness 0.88**   | + 5.6 %               | + 15.6 %              |
| **Thickness 0.82**   | + 14.6 %              | + 18.4 %              |

Another impact in a lower dead volume when the mesh number is increased: a bigger part of the cold regenerator is composed of stainless steel rather than void volume, leading to a lower porosity. This parameter is experimentally known, as presented in Table 2. As the dead volume is a drag to the performance because some of the additional oscillating flow it requires for the pressure variations, its decreasing therefore has a positive effect.

**Table 2.** Dead volume variation, compared with the reference geometry.

|                      | Half cold regenerator | Full cold regenerator |
|----------------------|-----------------------|-----------------------|
| **Thickness 0.88**   | - 3.2 %               | - 8.5 %               |
| **Thickness 0.82**   | - 8.1 %               | - 9.8 %               |

### 4.2. Negative effects measurements

The bigger number of meshes induces also mechanisms that have a negative impact on the performance: the conduction due to the mesh can increase, causing more parasitic heat loss on the cold tip. The pressure drop along the regenerator could also increase, reducing compression expansion ratio at the cold tip. We try to experimentally quantify these negative effects.

The parasitic heat loss represent the total heat loss reaching the cold tip, reducing the performance of the pulse tube cooler. It can be induced by convection, conduction or radiation. The experimental setup is designed to minimize the radiation thanks to screens and MLI. Because the cold part of the pulse tube is below the warmer part, the helium is considered static and convection is considered negligible. Conduction should be the greater contribution to the parasitic heat loss, through the two coaxial tubes seen in Figure 1, the helium and the stainless steel mesh. This loss has been experimentally measured using a “PV power decreasing method”, based on an extrapolation of performance with zero compressor input power given to the cold finger. This method, close to the one described in [8], is illustrated in Figure 7. We focused on the following conditions: cold tip at 15 K, intercept temperature regulated at 80 K and compressor frequency set at 43 Hz. Results are presented in Table 3.

![Figure 7](image-url)  

*Figure 7. Illustration of the “PV decreasing method” to estimate the parasitic heat loss at cold tip.*
Table 3: Experimental estimation of the parasitic heat loss on cold tip at 15 K.

| Thickness | Half cold regenerator | Full cold regenerator |
|-----------|-----------------------|-----------------------|
| 0.88      | 157 mW ± 10 mW        | 151 mW ± 10 mW        |
| 0.82      | 152 mW ± 10 mW        | 170 mW ± 10 mW        |

Unfortunately, the parasitic heat loss has not been measured for the reference configuration. It is still possible to compare the other configurations: taking into account a results uncertainties of ± 10 mW, the impact of the higher mesh number on the parasitic heat loss, and therefore on performance, seems limited.

Another parameter studied is the pressure drop through the regenerator. To estimate this pressure drop, a dedicated test bench is used. The measurements are made with DC flow at ambient temperature, what is not fully representative of the real conditions inside the pulse tube cooler but is relevant to compare the configurations. The pressure drop values are plotted in Figure 8.

![Figure 8. Pressure drop multiplied by the average pressure through the pulse tube cooler.](image_url)

An increase of the pressure drop is observed for the thinner mesh, what can be understood because the ratio solid matrix/void volume in the regenerator is bigger, making it harder for the gas to flow through it. This increase is more apparent for the full regenerator than the half regenerator because of the higher mesh number. The positives effects from dead volume reduction, specific heat and surface exchange increases previously presented are probably minimized by this increase of pressure drop.
The pulse tube cooler performance is a result of the competition between positive and negative contributions: the thinner the mesh is and the more filled the cold regenerator is, the better the performance should be thanks to the lower dead volume and the higher exchange surface and the matrix thermal capacity. But the induced increased pressure drop is going against it, making a prediction of the behavior difficult without conducting fully representative measurements.

5. Conclusion
This project, focusing on regenerator technology, evaluated the cold regenerator mesh geometry influence on the pulse tube performance. It required precise measurements of performance, validated by a thorough reproducibility study. An optimal mesh thickness has been highlighted, for each part of the regenerator, depending of the operation conditions like the cold temperature.

This behavior can be interpreted regarding the impact of the increasing number of meshes on some thermal parameters as the thermal capacity, the parasitic heat loss and the exchange surface; and on hydraulic parameters like the dead volume and the pressure drop.

As the behavior for a half and a full cold regenerator is different, an additional work would be interesting to perform on generator grading: on optimum mesh configuration would require filling it gradually with suitable thickness mesh, depending on local expected temperatures. More importantly, a combination of the presented results with materials study could improve significantly the 15 K pulse tube cooler performance.

The optimal mesh thickness highlighted in this study is specific to our conditions. This optimum, however, should exist in applications with different conditions (temperature, geometry…), even if the optimum value will be modified. The ratio between the thickness variation (18 % here) and the order of magnitude of the performance gain (1.5 K for the lowest temperature or 80 mW at 15 K) should then be comparable to the results presented here.

6. References
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