An efficient damper for thermal oscillations in two-stage Pulse Tube cryocoolers.

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Abstract

We have developed a passive system to efficiently reduce the amplitude of temperature oscillations in low-frequency Pulse Tube (PT) cryocoolers. It consists of a small, well-insulated tank of liquid ^{4}He, placed between the cold head of the PT and the user.

As a result, we have been able to reduce the amplitude of thermal oscillations by a factor of 192, from 173 mK to 0,9 mK.

The same damping efficiency can be obtained even if a thermal power of up to 100 mW is dissipated over it: the temperature oscillations remain consistently small as long as the Helium remains in its liquid phase.

Even after its transition to the gas phase, the thermal oscillations continue to be stable, and despite increasing in amplitude by one order of magnitude, reaching 9mK, they remain 19 times lower than those at the cold head of the PT.

The advantage of this tool resides in the fact that it is a small, very compact sealed Helium reservoir, free of moving parts and external links.

In addition, the design of our damper leads to very low thermal conductivity, which, combined with the thermal capacity of liquid Helium, results in a thermal time constant several orders of magnitude larger than the period of the PT. This thermal insulation represents the true innovation proposed by our system.

As a matter of fact, the presence of two stainless steel tubes guarantees efficient thermal isolation and ensures rapid cooldown of the thermally isolated pot (without increasing cooling time) starting from room temperature, the final temperature is able to be reached (is reached) in 140 minutes, the same time it takes to reach it in the absence of the damper.

Keywords

^{4}Helium, temperature oscillations, pulse-tube cryocooler, low temperature technology

Introduction

Our cryocooler is a hybrid system composed of an air cooled Sumitomo compressor (CSA-71) coupled to a TransMIT PT cryocooler (PTD406-C). Its cooling capacity at 4.2 K is about 1.5 W and the minimum temperature at zero load is below 3K. However, PT cryocoolers usually produce large temperature oscillations (>100 mK) at the cold head which are almost sinusoidal in shape and match the frequency of the PT (1,25 Hz).

In many cases this is not an issue, but there are situations in which a greater thermal stability is highly desirable, for example during tests and calibrations of detectors operating at cryogenic temperatures: typically, for these detectors, 100mW of available power is substantially more than necessary, but the temperature must be kept as stable as possible.

Several attempts have been made in the past to achieve this goal, using analogous techniques. Previous solutions had been able to produce peak-to-peak oscillation values of 50 mK [1]. With a compact, sealed, although non thermally isolated system, oscillations have been taken down to around 10 mK [2], and other authors have been able to achieve similar results [3], [4], [5], down to 3mK [6]. The use of rare-earth alloys, such as ErNi, allows temperature oscillations as low as 14,5 mK [7].

Results akin to our solution's were attained by Dubuis et al. who developed a damper that acts as a low-pass filter by inserting thin sheets of lead, stainless steel and copper between the cold head and the sample. This system is able to reach a final oscillation temperature of 0,1 mK [8], whereas conventionally, only through the implementation of active dampers employing reinforced plastic fiber has a level of temperature oscillation reduction of up to 0.2 mK been achieved. [9]

Our damper system is shown in Fig.1. A copper condenser plate P is anchored to the cold head of the PT. A small liquid ^{4}He reservoir E, a cylindrical container whose internal volume is about 28 cm^3, with an internal contact surface with liquid Helium of 10 cm^2, is connected to the plate P via two thin-walled stainless steel tubes (outer diameter 4.76 mm, 63 μm thickness, each 7 cm long) which provide good thermal insulation. The condenser P is also connected via a capillary tube C to an external Helium gas reservoir. In this way the amount of gas to be liquefied can be controlled. Two calibrated Lake Shore DT-670-CU-1.4LDT Silicon diode thermometers measure the temperatures of both the PT cold head and the L^{4}He pot E.

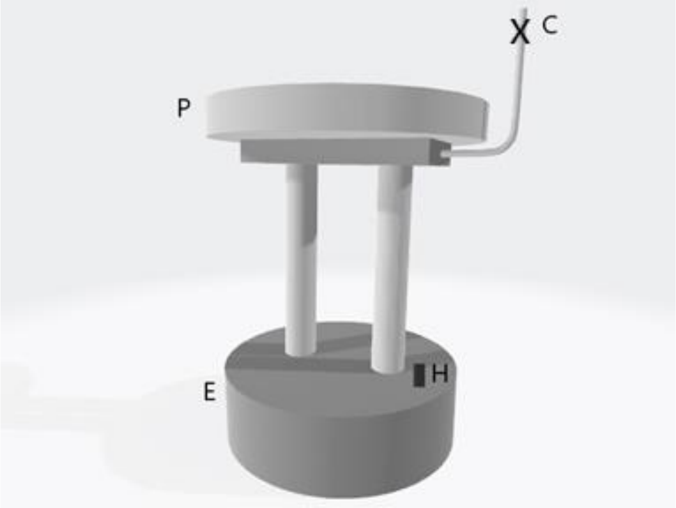

Figure 1 Schematic damper drawing. H is the heater

We carried out a number of measurements varying the volume of the L^{4}He from 26 cm^3 down to 3 cm^3. No cooling cycle was performed without Helium gas, because we estimate that in this condition it would take over 100 hours for the damper to reach the minimum temperature, due to the good thermal insulation of the He pot. As a matter of fact, the presence of two tubes connecting the LHe pot to the condenser plate P, ensures a rapid cooling of the pot, thanks to the convective circulation of gas in this two-way configuration [10].

Since no significant difference has been observed in the damping ability of the system while changing the amount of L^{4}He in the pot from 3 to 26 cm^3, we conclude that there is no need for a capillary tube connecting the condenser plate to an external Helium gas reservoir.

Therefore, it was decided to use a sealed Helium tank loaded to a pressure of 8 MPa. This solution proves to be more functional compared to other temperature oscillation damping methods. [4][5].

Figure 2 shows a schematic of our damper mounted on/attached to the cold head of the PT.

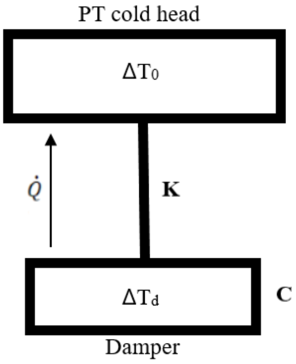

Figure 2 Schematic diagram of the damper mounted on the bottom of the PT head.

Where ΔT_0 and ΔT_d denote the temperature oscillations of the PT and the damper respectively. The heat flow between the damper and the PT is

$$\dot{Q} = \frac{2KA}{l}(\Delta T_d - \Delta T_0)$$

where $K = 0{,}2\ \frac{W}{mK}$ is the thermal conductivity of the two stainless steel tubes, A denotes their surface area and *l* their length.

In this case $A = 0{,}9 \text{ x}10^{-6}\ m^2$ and $l = 0{,}07$ m.

Let $\boldsymbol{k} = \frac{2KA}{l} = 5{,}4 \times 10^{-6}\,\frac{W}{K}$, then

$$\boldsymbol{k}(\Delta T_d - \Delta T_0) = \mathbf{C}\frac{d\Delta T}{dt} \qquad (1)$$

where C is the thermal capacity of helium. The solution to (1), which is comparable to the equation for exponential decay of the current through a capacitor in an RC discharging circuit (where $R = 1/\,\boldsymbol{k}$), is given by

$$\Delta T_d = \Delta T_0(1 - e^{\frac{-kt}{C}}) \qquad (2)$$

Knowing that the total volume occupied by helium at 300K, p = 8MPa is equal to $V = 31\ cm^3$, that $\bar{R} = 2077\ \frac{J}{KgK}$ is the specific gas constant of helium at the same temperature conditions, from the following

$$\frac{pV}{m} = \bar{R}T$$

we obtain *m* = 0,4 g, from which $\boldsymbol{C} = mc = 2{,}1\ \frac{J}{K}$ with $c = 5193\,\frac{J}{KgK}$ being the specific heat of the liquid helium.

Extracting $\Delta T_0 = 173\ mK$ from (2), we can combine the previous steps to deduce the final value of $\Delta T_d = 1{,}04$ mK, which is entirely in line with our experimentally obtained result of 0.9 mK.

Both the analytical approach and measurements carried out prove that varying the volume of the L^4He from 3 to 26 cm^3 does not produce any appreciable variation in the final result, due to the fact that ***C*** isn't the leading-order term in the ***k*** **/*C*** relationship in equation (2), confirming thermal isolation to be the key strength of our damper.

Increasing the volume of Helium, and therefore thermal capacity *C*, would further reduce the temperature oscillations, at the expense of the compactness of our system, while reducing the thermal conductivity *k* would not cause substantial variations to its geometry.

Performance

Once the whole system is cooled below the critical point for ^{4}He (5.2 K), the gas liquefies and drops into the pot, where the liquid is in equilibrium with its own vapour and the temperature rapidly reaches about 3K. The entire cooling process, starting from room temperature, lasts about 140 minutes. Figure 3 shows the final 90 minutes of a typical cooling process: the grey band represents the temperature oscillations of the PT cold head.

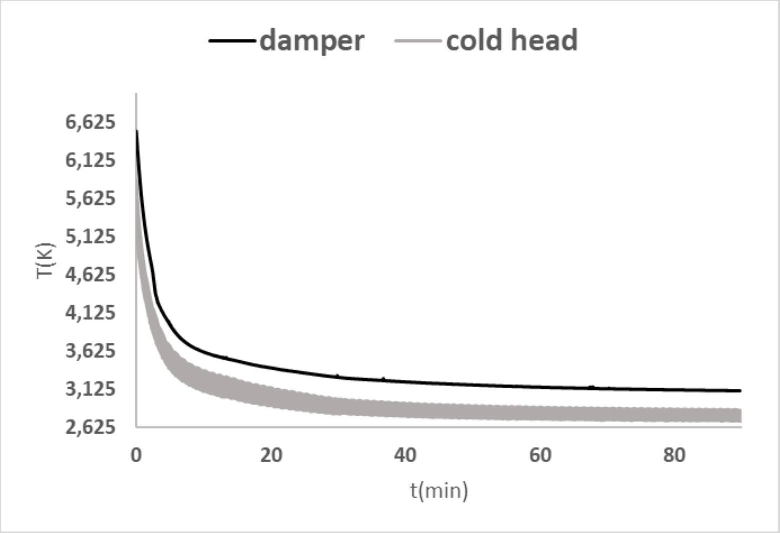

Figure 3 Cold head and damper temperatures versus time during cooldown. Solid line: damper oscillations. Continuous band: cold head oscillations.

These oscillations have a peak-to-peak amplitude of about 173 mK, as shown in Fig.4, where an interval of 5 seconds is reported.

The continuous line represents the temperature oscillations of the damper, which are contained in less than 1 mK peak-to-peak, at least two orders of magnitude smaller than those of the cold head.

This is shown in Fig.5 for the same 5 seconds interval as before.

From Fig.3 one may also note that the average temperature of the damper is a bit higher than the average temperature of the cold head.

This temperature gradient can be attributed to the low thermal conductivity of the two stainless steel tubes.

However, it is due to this thermal insulation that the system is so efficient

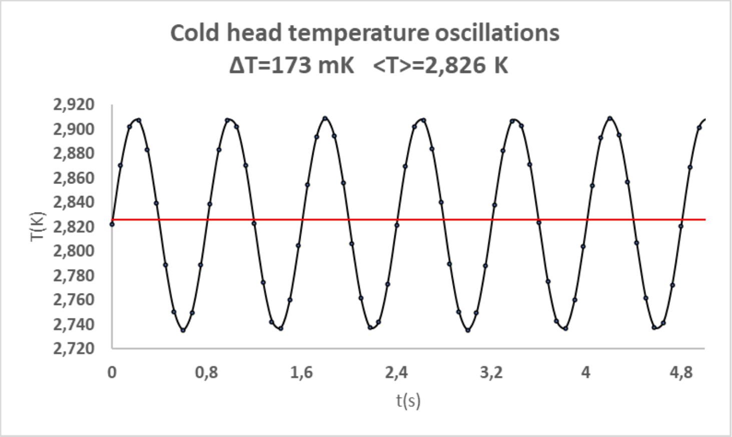

Figure 4 PT Cold head peak-to-peak temperature oscillations

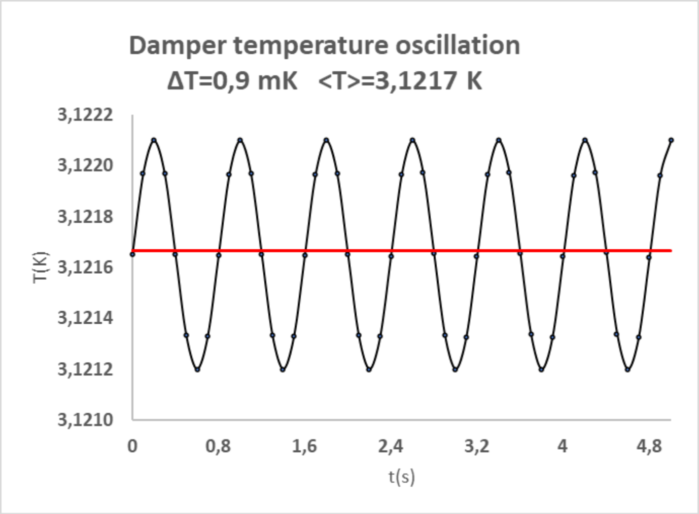

Figure 4 Damper peak-to-peak temperature oscillations

Figure 6 shows the damper's temperature variation in relation to changes in dissipated power.

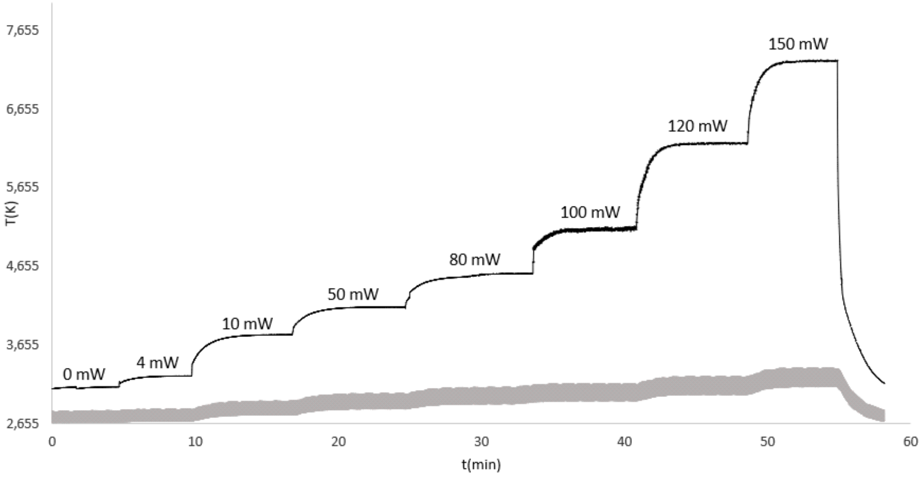

Figure 6 Warming cycle: when the dissipated power reaches 100 mW the oscillations increase due to the Helium phase transitioning from liquid to gas.

The cold head's temperature follows the heating of the damper, but this variation is negligible for the high cooling power of the PT-Transmit cryocooler.
Table 7 shows temperature oscillations vs dissipated power on the damper

Dissipated power (mW)	Average temperature (K)	Temperature Oscillations (mK)
0	3,1217	0,9
4	3,2698	0,9
10	3,7832	0,9
50	4,1363	0,9
80	4,5135	0,9
100	5,122	37 *
120	6,217	9
150	7,237	9

Table 7 Damper temperature oscillations versus dissipated power. *Phase transition

During the liquid-to-gas phase transition, the temperature oscillations reach an amplitude of about 40 mK, however they always remain lower than those in the cold head. In the gas phase, the oscillations are equal to 9 mK. Even in case of a rapid increase in temperature, the system was able to become stable again and could be operated in this temperature range, albeit with oscillations one order of magnitude higher than those of the liquid phase.

Conclusions

This damper, in addition to being very easily manufactured, allows to reduce the amplitude of thermal oscillations in PT coolers by at least two orders of magnitude. As long as the thermal power dissipation remains within 100 mW, the system can be used with oscillations of less than 1 mK. Nonetheless, the performance of this prototype could be further optimized by modifying the thermal insulation between the E pot and the PT cold head.
Without any need to make major modifications that would change the handling of the damper, it is possible to vary the thermal conductivity ***k*** to make the system adaptable to a variety of applications.

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Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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