Materials for damping the PTC-induced thermal fluctuations of the cold-head

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Abstract

The cold head on mechanical Pulse Tube Cryocoolers (PTCs) is subject to substantially less mechanical vibration and electromagnetic interference compared to that typically found in Gifford MacMahon coolers. However, thermal fluctuations at the PTC frequency are still present at the cold-head, typically at a level of 200 mK peak-to-peak at 1.4 Hz for a Cryomech Model PT405 cooler running at 4 K. It is highly desirable to damp out these fluctuations if PTCs are to be used successfully for running systems sensitive to such thermal fluctuations, for example, bolometric detectors.

We report here the characterization over the temperature range 2.5 K to 6 K of two materials, GOS (Gd₂O₂S) and GAP (GdAlO₃), for use as low-pass thermal filters. These materials have antiferromagnetic transitions at around 4 K giving rise to an enhanced heat capacity and have a high thermal conductance. These are two highly desirable properties for thermal dampers in this application. Those materials were fired as ceramic discs to be tested as thermal dumpers. Thermal filter assemblies with discs of diameter 75 mm and thickness 2.5 mm and 1.6 mm (GOS and GAP, respectively) mounted in a PTC show thermal attenuation levels of x0.12 (GOS) and x0.11 (GAP) at 0.01Hz with a clean-side temperature of 4 K; the PTC induced fluctuations at 1.48 Hz are damped completely to within the noise limits (0.2 mK) of the thermometers. Experimentally determined thermal conductance and heat capacity data are reported. For this system, with a PTC cold-head (dirty-side) temperature of 3.3 K, a clean-side power dissipation of up to 30 mW is realized before its temperature rises above 4.2 K.

Introduction

The 4 K cooling method using regenerative cryocoolers is very attractive when compared to the use of a liquid helium bath. Such cryocoolers provide autonomy of the cooling source using a lower cost and greener solution. Intrinsically for their use in thermodynamic cycles, there are oscillations associated to some extent, both thermal and mechanical. Pulse Tube Cryocoolers (PTC) having no moving parts at low temperature significantly reduce the mechanical issue, but not the thermal one.

The addition of a thermal buffer to the cold end is a solution to stabilize the thermal oscillation of the cold source. The trade off between maximizing the heat capacity to stabilize the temperature while having a good conductance to prevent a major loss of performance of the cooler is a challenge. Keeping the system simple is also desirable.
A vibration isolation and thermal damper for a 4 K GM cooler was reported in ref [1], although without details of its composition, showing to be able to reduce the 200 mK at 3.5 K oscillation down to 1 mK at 4.1 K. A report on the addition of 3.6 mm plates of ErNi in a 4 K PTC have shown a reduction from 275 mK to 14.5 mK [2] on the temperature oscillations. The ErNi material exhibits a ferromagnetic transition at about 10.5 K, hence not reflecting its high heat capacity peak on the 4 K temperature range. The cooling power became halved upon addition of such buffer. That work found an effective thermal conductance about a factor of 10 lower than the reported value for the bulk [3]. Other recent work on the same subject explored the heat capacity of a superconductor transition [4]: Lead with its critical temperature of ~8 K was chosen, that metal being combined with others in a stack of thin sheets on the cold head of a GM 4 K cooler and tested up to 50 K. At 4 K the 1.2 Hz oscillation of temperature was reduced from ~30 mK to 1 mK. Adding this buffer led to a double in cooldown time, its lower achieved temperature being 3.4 K instead of 3.0 K.

We investigated the use of bulk ceramic materials developed for use in regenerators, such as GOS = Gd₂O₂S and GAP = GdAlO₃ [5-7] as temperature dampers in a 4 K Cryomech PT405 pulse tube cryocooler. Such materials exhibit especially high heat capacity at the interesting 4 – 5 K [8-10] range, due to a para-antiferromagnetic transition, with quite high reported conductivity [5].

This paper presents the experiments performed with GOS and GAP discs as temperature fluctuation dampers. Data on effective thermal conductance for both GOS and GAP samples is reported from 3 K to 6 K. Temperature oscillations at the cryocooler’s 1.48 Hz frequency vanishes to the noise level by using either material in. Lower frequency values are tested in an oscillatory heating of one side of each disc, for different temperatures. A gain to frequency Bode-type diagram is reported while the analogy with a standard passive resistor-capacitor circuit (RC) type filter fitting is explored. The extrapolation of cutoff frequency values from that diagram yields a preliminary result on the conductance to heat capacity ratio of the materials used.

**Experimental setup**

The sample assembly is shown in Figures 1 and 2. The Sample (GOS or GAP disc) is sandwiched between two copper plates (Top and Bottom Plates). A G10 ring is used to compress the Sample against the copper plates. The Bottom Plate is bolted directly to the cold finger of a cryocooler (Cryomech PT-405). The Sample to Plate interfaces have a smear of vacuum grease. The Bottom Plate to PTC Cold Head is a grease-free interface. Each Plate has a heater \(H\), of 200 \(\Omega\) nominal value) and a germanium Lake Shore calibrated temperature sensor \(T\).

Two 75 mm diameter discs were used as the Sample, one GAP disc with 1.6 mm thickness and one GOS disc with 2.5 mm thickness. The thicknesses were designed so the samples’ conductances could match about 1 W/K conductance [5], regardless of the contact resistance.

The effective conductance \(K\) is measured by applying a small power (0.02 W and 0.03 W) to the Top Plate through heater \(H^{\text{top}}\) and stepping the power in the Bottom Plate, \(H^{\text{bottom}}\). Data is collected at each step for typically 600 s using a AVS47 IEEE 488 interface.

The frequency response of the thermometers is measured using the faster analog output port of the resistance bridge, read by a 24-bit NI DAQ card while modulating the temperature of the bottom plate at a known frequency using \(H^{\text{bottom}}\). This is done at four frequencies (0 Hz, 0.01 Hz, 0.02 Hz and 0.05 Hz) and for different DC power levels on \(H^{\text{bottom}}\).
Figure 1. Partial cut of the sample mounting as designed with SolidWorks™.

Figure 2. Schema for thermometers and heaters placements.

Figure 3. Assembly on the cold head of the PTC.

Experimental results
The ratio of \((H^{\text{top}} - H^{\text{bottom}})\) to \((T^{\text{top}} - T^{\text{bottom}})\) is assigned as the effective conductance \((K)\) at the average temperature for the arrangement of the measurements performed, and is displayed in Figure 4. Considering that the main thermal resistance is due to the sample disc — i.e., disregarding the copper resistance (about 4 orders of magnitude lower, in a conservative estimate) as well as the contact resistances (that may have a significant role), the experimental conductance along with the sample dimensions allows estimating the conductivity \((k)\) of the sample material, as plotted in Figure 5. Such conductivity comes about two orders of magnitude lower than reported by the manufacturer [5], which is plotted as dashed lines in the same figure.
Figure 4. Effective conductance measured.

Figure 5. Inferred conductivity for GOS and GAP discs and comparison to the manufacturer data [5].

Figure 6 displays one example of the induced oscillating temperatures logged on both sides of the assembly. The attenuation $G$ takes the ratio of bottom to top temperatures and was measured at different frequencies. The plot of the attenuation as a function of frequency is represented in Figure 7, for GOS and GAP respectively. Such attenuation approximately follows a single pole filter and a corresponding equation 1 fitting was performed. The adjustment of this equation to the attenuation measured at each frequency gives rise to the cutoff frequencies $f_0 (f_0 = K/2\pi C)$ plotted in Figures 9 and 10.

$$\frac{T_{top}}{T_{bottom}} = \frac{1}{\sqrt{1 + \left(\frac{f}{f_0}\right)^2}}$$

(1)

The phase shift for such first order filter shall follow equation 2, and not surpass -90°:

$$\phi = -\arctan\left(\frac{f}{f_0}\right)$$

(2)

Figure 6. Example of induced oscillations on bottom plate and respective attenuation on top plate.
Attenuation analysis is plotted in Figure 7 as a Bode-type gain plot, both for GOS and GAP. The adjustment of equation 1 to the 0.1 Hz and 0.01 Hz points at each measured temperature determines the cutoff frequency \( f_0 \) as plotted in Figure 8. One can see that both sets of values for \( f_0 \) are in agreement, while taken from different frequencies. Such adjustment is equivalent to the extrapolation up to \( G = 1 \) of the fitted slope (corresponding to a first order filter) as in the dashed long line in Figure 7. The best-fitted slope would be slightly steeper than this, which is ascribed to the fact that the current assembly constitutes a distributed system, not exactly a simple RC as in this model. The phase shift analysis yields more than -90° for most points, realizing that the first order model is just an approximation to this system.

**Figure 7.** Attenuation of the induced oscillations for GOS (left) and GAP (right) as a function of frequency. The dashed long line emphasises the expected slope for a first order filter — its fitting to each temperature along with an extrapolation back to \( G = 1 \) confirms the cutoff frequency values determined from equation 1.

**Figure 8.** Cutoff frequencies as fitted by equation 1, for GOS (left) and GAP (right).

Using the experimental conductance values (\( K \)) along with the cutoff frequencies (\( f_0 \)), the heat capacity (\( C \)) can be calculated and is depicted in Figure 9. For both materials the curve shape reproduces well the reference data [5] but there is about 50% of heat capacity missing. Actually the measured cutoff frequencies provide the information of the heat capacity and the heat conductance of the whole assembly, in a combined circuit.

Each sample disc provides most of the total heat capacity, the copper top plate adding only about 1% at the peak temperatures to the ceramic and the grease layer (1 mm\(^3\) estimated) adds less than 0.1% of the sample heat capacity. This way it is about 98% accurate to consider the peak heat capacity of the whole assembly as the sample property.
The experimental values for thermal resistance add the resistance of the copper blocks to the sample discs as well as all the contact resistances. If the copper block’s contribution to the whole resistance is negligible, the same cannot be said about the three contact resistances: copper-grease-sample (twice) and copper-copper. Contact resistances are to be analysed and improved. The observed discrepancy on thermal conductivity may also be due to the fact that the manufacturing process of the discs did not exactly match the same protocol as the materials reported in ref [5]: a heat treatment was missing, which should lead to a grain increase and consequent conductance increase [11]. The related work on ErNi [2] also reported a significant reduction on the experimental effective thermal conductance, suggesting the existence of more than one single phase of the material apart from contact resistance added.

Indeed the thermal system is harder to model, but even so, the performed experiments suggest a promising quite simple new method for measurement of low temperature heat capacity.

![Figure 9](image)

Figure 9. Specific heat capacity $c$ for GOS and GAP materials obtained from the cutoff frequency values and comparison to Numazawa’s reference data [5].

**Conclusions**

Aiming to strongly reduce the temperature oscillations of a Pulse Tube cryocooler, a thin disc (2.5 and 1.6 mm thick) of high heat capacity material, GOS and GAP, was added to the cold finger, acting as a low pass thermal filter. The geometry of the discs was designed to yield about 1W/K conductance at ~4 K but failed by two orders of magnitude. The conductance issue needs improvement, namely on the contact interfaces.

A Bode-type diagram evidences filtering at the cryocoolers’ operating frequencies. The approximation to a first order Butterworth filter allows assigning a cutoff frequency as in a single pole thermal $RC$ circuit. The inferred specific heat capacity confirms the abnormal peak on heat capacities but comes reduced to about one half of the expected values.

The coupling of a thin disc of GOS or GAP material to the cold end of such a cryocooler brings several (>2) orders of magnitude reduction in the temperature oscillations at 4 K induced by the normal operating frequencies of such machines.
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