# Improvement of a Two-Stage 4-K Pulse Tube Cryocooler with Low Input Power and Comparison to Numerical Simulation

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## ABSTRACT

A numerical model has been constructed by use of the Sage software, which was used to calculate a two-stage 4 K GM-type pulse tube cryocooler with a low input power of about 1 kW. The cryocooler was initially designed for cooling of single photon detectors at 5 K and has recently been improved for the usage at 4 K. The geometry and regenerator matrix are optimized in two steps in order to increase the cryocooler's cooling performance. The overall coefficient of performance has been doubled. For each step, a prototype of the cryocooler was manufactured and tested. The data are compared to the corresponding numerical calculations. The cooling powers from simulation are in good agreement with the experimental findings. The numerical models now give insight on the changing thermodynamic parameters due to improved geometry and regenerator matrix.

## INTRODUCTION

The development and optimization of a new cryocooler working at liquid helium temperature is often a long and time-consuming process that can be supported and improved by using suitable numerical software. The generated models can provide insight to specific details of the analyzed system or try to represent the whole system.[1,2] The numerical simulation software Sage[3] is often chosen and appropriate for the representation of complete cryogenic systems such as pulse tube cryocoolers (PTC), but difficulties with convergence in the range of liquid helium temperatures are well known. Nonetheless, this work proves it to be a powerful tool for analyzing complete low temperature systems down to 4 K. We have used the low input power 4 K Gifford-McMahon-type two-stage PTC named "SUSY" to construct a numerical model.[4]

Furthermore, we report on the improvements made to the PTC to increase the coefficient of performance. The experimental data verify the calculations made by the software to provide a reasonable model for further constructions and optimization.[5]

## CRYOCOOLER AND SETUP

The previously reported pulse tube cryocooler "SUSY" was modified in two steps based on the measured performance data of the first version.

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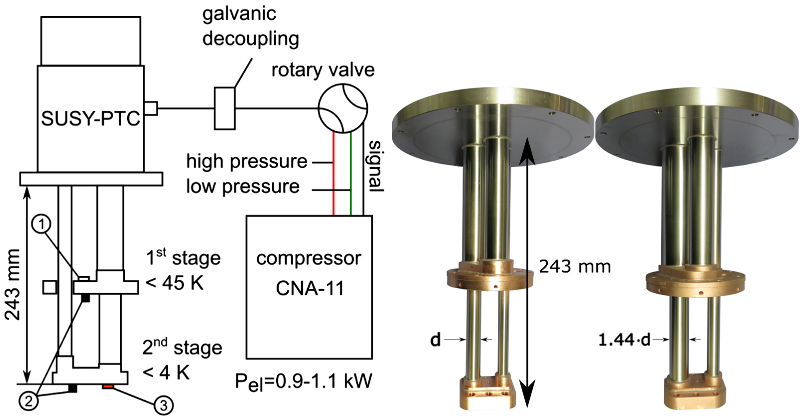


(a) (b)

**Figure 1.** (a) Schematic drawing of the experimental setup with PTC "SUSY". The PTC is driven by a SHI CNA-11 with an electrical input power of 0.9 to 1.1 kW. The rotary valve generates the necessary pressure wave for the PTC. The compressor is galvanic decoupled from the cold head. The copper heat exchanger of the two stage system are equipped with temperature sensors and electrical heaters for characterization. (b) Photograph of SUSY vers. 1.1 and vers. 2.1 indicating the increased tube diameter with constant overall length.

All versions are driven by a CNA-11 compressor (Sumitomo heavy industries, inc.) as shown in Fig. 1 with a filling pressure of 18 bar helium (6.0). The electrical power consumption ranges from 0.9 to 1.1 kW. The rotary valve was set to a working frequency of 2 Hz during measurements. The cold head is equipped with a Pt100 (JUMO) temperature sensor at the 1st stage heat exchanger (1) and a Cernox® (Lake Shore Cryotronics, inc.) temperature sensor at the 2nd stage heat exchanger (3). The resulting cooling power is measured by applying a heat load through electrical heater (2) at both stages. Both stages were thermally insulated by several layers of aluminized Mylar foil. The 2nd stage was encapsulated by a copper radiation shield, which was attached to the 1st stage heat exchanger and also wrapped by several layers of Mylar foil.

With the experience gained from the first measurements, we have concluded that the mass flow generated by the compressor is too high for the small tube diameters. Therefore, the first step was to increase the tube diameters by a factor of up to 1.44 (see Fig. 2) while keeping the overall length constant at 243 mm. The increased tube diameter should allow a higher mass flow towards the first and second stage of the cryocooler, thus resulting in a higher cooling power. The constructed PTC is shown on the right hand side in Fig. 2 and will be called "SUSY 2.1".

The initial cryocooler was designed for temperatures of 5 K as mentioned in the introduction. The regenerator matrix was therefore filled with $HoCu_2$ and $Er_3Ni$ to achieve highest cooling performance at 5 K. The second step was to adapt the regenerator matrix for temperatures below 4.2 K by including GOS ($Gd_2O_2S$) in the coldest part of the regenerator.[6] This has been done with the SUSY 2.1 and the resulting design will be called "SUSY 2.2".

The three mentioned types of cryocooler were implemented in the numerical simulation software SAGE to verify the simulation model trough the improvement process. The performed improvements will be analyzed and compared to the numeric calculations.

## COOLING PERFORMANCE

The above described PTCs show the expected improvement in the measured cooling performance. This behavior can be seen in Fig. 2 (a) and (b) showing "load maps" of the three PTC versions. The measured temperatures of the 1st and 2nd stages at thermal equilibrium while applying electrical heat load are plotted against each other. The corresponding heat loads applied to the 1st and 2nd stages are indicated by labels at the individual branches of the load maps in the diagram.

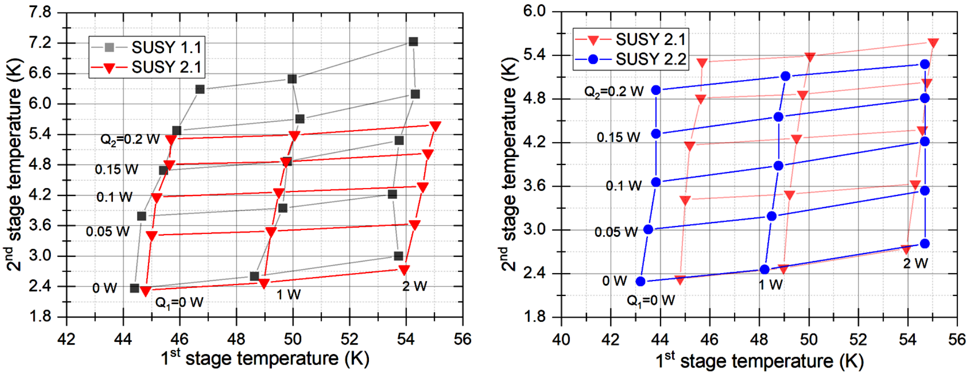


**Figure 2.** Loadmaps: (a) SUSY 1.1 (grey squares) and 2.1 (red triangles) with difference in tube diameter. (b) SUSY 2.1 (faded red triangles) and 2.2 (blue circles) including GOS as regenerator material in the 2nd stage regenerator.

In Figure 2 (a) the load maps of SUSY 1.1 and 2.1 are displayed. The overall temperature of the 1st stage is similar for both versions between 44 and 56 K for an electrical heat load of up to two watts. The increased tube diameter visibly decreased the 2nd stage temperature for identical heat loads of up to 200 mW. The cooling power at 4.2 K has been increased from roughly 73 mW up to 103 mW.

The resulting change in cooling power for the regenerator matrix with GOS is shown in Fig. 2 (b). The 1st stage temperature is slightly reduced from version 2.1 to 2.2. The 2nd stage temperature is also reduced resulting in a cooling power of 142 mW at 4.2 K. All three versions achieve a minimal temperature of approx. 2.3 K. Overall, the cooling power has been increased by a factor of almost two at 4.2 K, resulting in a coefficient of performance of $1.55\times10^{-4}$ at an electrical power consumption of 916 W.

## SIMULATION SOFTWARE SAGE

A numerical model has been constructed in the simulation software Sage for the three PTC versions and their changed parameters. With the calculated results it is possible to draw conclusions on the adjustments made. Also the results will verify the constructed numerical model for future improvements.

Figure 3 shows an example of the graphical representation of the numerical model in Sage of the SUSY 2.2. The arrows in the upper part indicate the mass flow through the system starting from the compressor with rotary valve (a) through a metal pipe (main inlet) into the 1st stage (b) and then to the 2nd

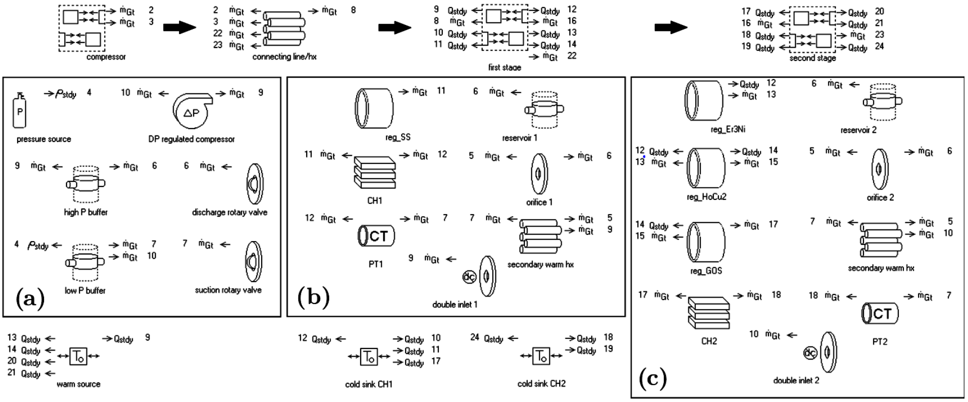
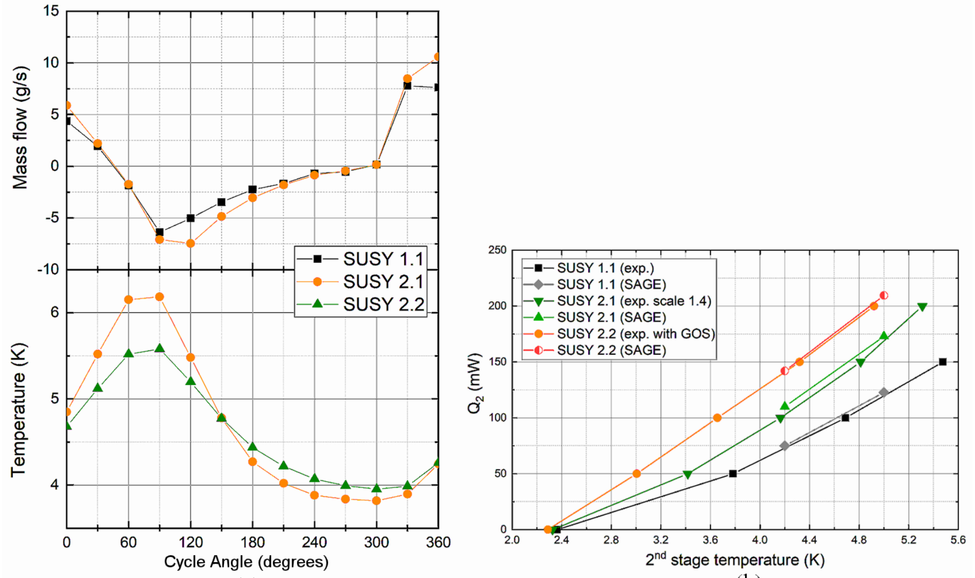


**Figure 3.** Graphical interface overview of the numerical simulation model for SUSY 2.2 consisting of (a) Compressor, flex lines, and rotary valve, (b) 1st stage regenerator (stainless steel sieves), double inlet, orifice, reservoir, heat exchangers and pulse tube, and (c) 2nd stage regenerator ($Er_3Ni$, $HoCu_2$, GOS), double inlet, orifice, reservoir, heat exchangers and pulse tube.



(a) (b)

**Figure 4.** (a) Calculated mass flow by Sage(upper) at the main inlet and temperature (lower) at the end of the 2nd stage regenerator over one cycle. (b) Experimental and calculated cooling power over temperature for all three PTC versions.

stage (c) of the cryocooler. The working frequency was set to 2 Hz in accordance with the experimental setup. It is to mention that in the 2nd stage the regenerator material GOS was not implemented in the cryocooler version 1.1 and 2.1.

The compressor is set to the pressure stroke given by the before mentioned CNA-11 helium compressor. The pressure stroke at the main inlet was measured to be 1.12 MPa and the numerically calculated pressure stroke is 0.97 MPa, both at a 2nd stage temperature of 10 K.

Improvements were made to tube diameter and regenerator filling. First the increased tube diameter will be investigated with the numerical model. The implemented compressor function is chosen to be pressure-stroke regulated; this means the software calculates the resulting mass flow to achieve the set pressure stroke. Increasing the tube diameter should then increase the mass flow through the system. This can be seen in the upper part of Fig. 4 (a). In the graph the mass flow at the main inlet is plotted over the last cycle. The calculated mass flow over the last cycle changed with an increased area below the curve from SUSY 1.1 (black squares) to SUSY 2.1 (orange circles). The suggested effect of the first change can therefore be seen in the calculations.

The second improvement was changing the regenerator materials and adding GOS. The volumetric specific heat of GOS is higher than that of $Er_3Ni$ and should therefore increase cooling performance when used at the lowest expected temperature. This can be seen in the calculations in the lower part of Fig. 4 (a). The calculated temperature at the end of the 2nd regenerator (beginning of the 2nd stage heat exchanger) is plotted over one cycle. The amplitude of the temperature curve for SUSY 2.1 (orange circles) is higher than SUSY 2.2 (green triangles) over the whole cycle. With the increased volumetric heat capacity of GOS the change in temperature with identical heat flow should decrease as shown in the plot. This is in good agreement to the anticipated and measured behavior of the cryocooler.

The calculated and measured cooling powers of the 2nd stage can be compared and are displayed in Figure 4 (b). The measured and numerically simulated heat loads are plotted over the temperature of the 2nd stage heat exchanger. The so-called load curves indicate the increased cooling performance of the cryocooler over the three versions. The cooling power of the numerical model is calculated for 4.2 K and 5 K. The calculated values exhibit a minor offset compared to the experimental data.

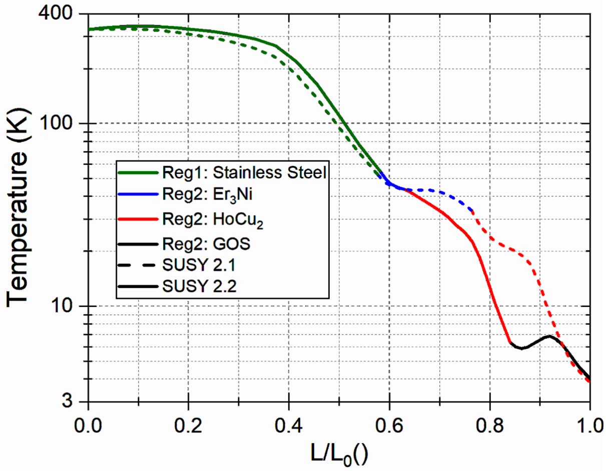


**Figure 5.** By Sage calculated temperature profile along the regenerator of SUSY 2.1 (dashed lines) and 2.2 (continuous line). Colors indicate the implemented regenerator material (green – stainless steel sieves; blue – Er3Ni; red – HoCu2; black – GOS)

The numerical models can now be analyzed to give further insight into pulse tube cryocooler. In Fig. 5 the temperature profiles of SUSY 2.1 (dashed line) and 2.2 (continuous line) along the cryocooler are plotted over the normalized length.

The temperature profile of the 1st stage is similar for both cryocoolers due to the identical regenerator material consisting of stainless steel meshes (green). The temperature slightly decreases over the first 30 percent and then the curve declines down to 45 K at the 1st stage heat exchanger.

Along the 2nd stage the temperature profile differs. Most of the $Er_3Ni$ has been exchanged by GOS at the lower end of the cryocooler SUSY 2.2. Remarkably the calculated temperature profile provides a peak at the middle of the GOS section around 5 to 6 K.

This effect is due to the relatively high heat transfer rate of GOS at this temperature, which has been proven by Fang et al.[7] They state that the amount of GOS in the regenerator experiences a maximum in efficiency and more material can lead to a significant decrease of the cooling performance.

## CONCLUSION

We have demonstrated an improved PTC through two steps. By increasing the tube diameter and adding GOS in the 2nd stage cryocooler the cooling power increased from 73 mW to 142 mW; this resulted in a doubled coefficient of performance. The acquired experimental data were implemented in a numerical simulation model in the software Sage. The calculated cooling power is in accordance to the measured values.

Furthermore, the suggestions made to improve the cryocooler can be represented by the calculations of the numerical model. This gives the opportunity for further improvements and deeper insight into the cryocooler. The calculated temperature profile of the model is in good agreement to recently published literature.

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