

A Three-Stage Stirling Pulse Tube Cryocooler Approaching 4 K

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ABSTRACT

It is a great challenge for a Stirling Pulse tube cryocooler (PTC) to reach liquid-helium temperature, where there are promising applications such as superconducting digital electronics, mid-infrared instrument, heterodyne detectors. Lockheed Martin first achieved a temperature below 4 K with a four-stage configuration with He-3 as working fluid. A single-stage Stirling PTC precooled by a self-made two-stage GM-type PTC has been constructed and tested to explore the loss mechanism of 4 K PTC working at high frequency at Zhejiang University. Temperature as low as 4.2 K has been successfully obtained with He-4 as working fluid by the end of 2008. In this paper, we report a newly-designed three-stage PTC, which aims to reach 4 K. The 4 K cooler is a thermal-coupled type, whose mass flows are easier to control and whose energy flows are more readily monitored. It will be working with He-4 instead of He-3. The first and second stages have been finished. A bottom temperature of 35 K and 9 W at 77 K with 300 W input has been achieved in the first stage. The bottom temperature of second stage is as low as 20.6 K, and the cooling power is measured as 1.0 W at 28.6 K. The test results are in good agreement with the model for both stages. The first and second stage is designed to couple with the a stage, which is expected to reach below 5.0 K at 30 Hz.

INTRODUCTION

Low-temperature Stirling Pulse Tube Cryocoolers (SPTC) have become a hot topic recently¹⁻⁴. There are mainly two reasons. One is the technique requirement, which comes from the extended application^{5,6}. The other important reason is that, it is of a scientific interest for basic research⁷: the regenerative capacity, real gas effect, phase shift mechanism at low temperature region, and especially, challenging the lowest temperature. It seems to be a new round of "Liquid-He Temperature Competition", following GM type⁸⁻¹², about one decade later.

We have been extending the research to Stirling PTC for several years^{13,14}. In 2008, a precooled SPTC reached as low as 4.23 K in our group⁷. We began to design the three-stage SPTC to further simplify the configuration of 4 K pulse tube coolers since the end of 2008. It is of thermal-coupled type, and each stage can be detached. We test the cryocooler stage by stage, so as to analyze the performance of each stage clearly.

DESIGN OF THE THREE-STAGE PTC

A three-stage Stirling PTC is proposed to investigate the cooling mechanism at different temperature ranges. The three separated stages operate at LN₂, LH₂, LHe temperatures, which are all important temperature ranges for cryogenics. The thermal-coupled structure employs three thermal bridges to connect these stages. Each thermal bridge is detachable, which is convenient for assembling. It also allows for a straight forward independent calibration of its thermal resistance, which is helpful for the energy analysis. A schematic view of the three stage is shown in Figure 1.

Two compressors are employed to drive the three stages. The basic operating parameters are listed in Table 1. A high frequency and high charging pressure enables a high power density of the PTC working at liquid nitrogen temperature, while a low frequency and low charging pressure is quite favorable for low temperature operation. A typical 30 Hz and 1.0 MPa is chosen for the third stage. The goal is to reach below 5 K.

Temperature arrangement. Temperature arrangement of staged cooler is often of much concern. It is found that the first stage temperature between 120 K and 60 K does not affect the performance of the second stage much, for the structure with phase shifter located at ambient temperature¹⁵. While the lowest temperature available of the third stage with cold phase shifter is a strong function of the second stage temperature. A summary of the experiment results of near-4 K Stirling PTC is shown in Figure 2. It is seen that a precooling temperature as low as 8 K is required to achieve 4.2 K, with He-4 as working fluid. While the precooling temperature can be much higher for He-3.

In our design, a precooling temperature of 20 K of the second stage is set to meet the requirement of the third stage. The bottom temperature is estimated to be 4.9 K.

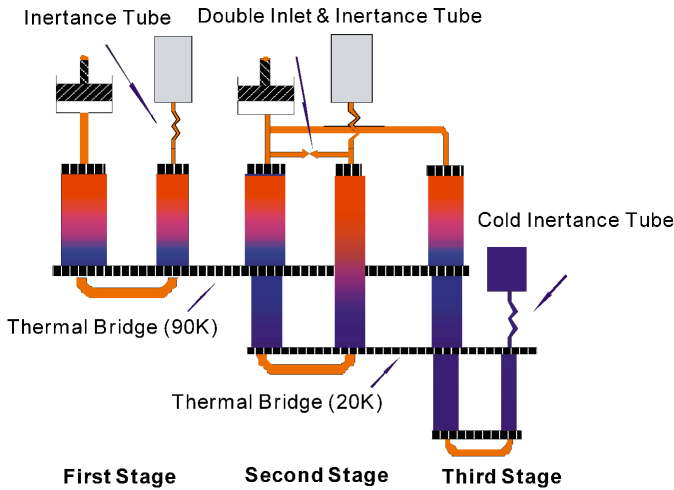


Figure 1. Sketch of the proposed three stage PTC

Table 1. Working parameter of the proposed three-stage PTC

Parameter	1st stage	2nd stage	3rd stage
Frequency (Hz)	40	30	30
Mean pressure (MPa)	2.0	1.0	1.0
PV Input power (W)	250	170	60
Bottom temperature (K)	37	11	4.9
Cooling power	15W@80K	1.4W@20K	60mW@6K
Relative Carnot	16.5%	11.5%	4.9%
Required precooling	None	8W@90K	4.5W@90K 1.2W@20K

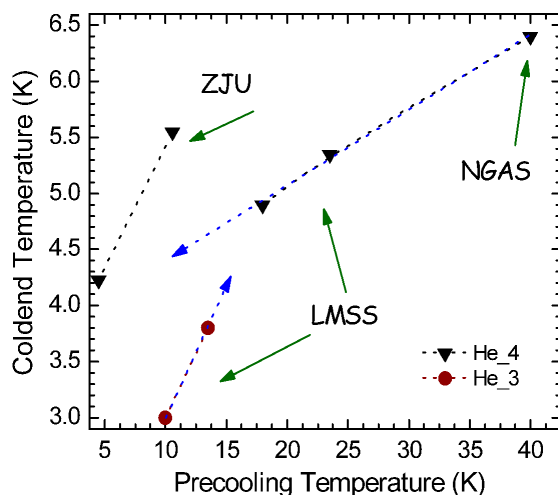


Figure 2. Lowest temperature versus precooling temperature

Regenerator. The regenerator is the key component of the PTC. The regenerative material should keep a balance between heat capacity and flow resistance. We select the matrix by temperature in all the stages. For temperature range between 300 K and 90 K, we use 400 mesh stainless steel screen, which is of relative high porosity, with a low flow resistance. For 90 K to 20 K range, we use layered 500 mesh and 635 mesh to enhance the heat transfer efficiency and heat capacity. Below 20 K, rare earth material is essential since the regenerative heat capacity become crucial. HoCu₂ powder with a mean diameter of 0.1 mm is used, which is among the best single-layered materials¹⁶.

Phase shifter. The phase shifter is another important component. An inertance tube is the most favorable phase shifter for Stirling PTC since it usually produces large phase shifting, without any DC flow. For the first stage, there is a large PV flow, For the second stage, the PV power at the inlet of the inertance tube turns to be quite small as the temperature goes down below 20 K, so a double-inlet valve is added to assist the inertance tube with phase shifting. For the third stage, the PV power decreases even more dramatically, while a cold inertance tube provides a relative large phase shifting.

EXPERIMENT TEST OF THE FIRST STAGE

The first stage should provide a large heat lift since its mission is to precool the second and the third stage. As large as 15 W at 80 K is available with 250 W of PV power input. The detailed description follows.

The first stage operates at 40 Hz and 2 MPa. A high frequency and a high charging pressure means a high power density. It could be higher but is limited by our compressor. The first and second stage could be driven by one compressor, but a large difference of the working condition will result in a poor performance for the first stage.

The first stage is optimized based on our model. The optimized dimensions are listed in Table 2, a serial inertance tube is applied for better phase shifting. The reservoir is a cylinder with a volume of 500 cc. The setup of the cold head is presented in Figure 3.

Since there is no DC flow induced by the inertance tube, it is quite stable. It takes about 20 minutes to reach 80 K with an input power of 300 We, and about 1 hour down to the bottom temperature of 38.6 K, as presented in Figure 4. The cooling power is 8.2 W at 77 K, with an input power of 300 We, and 12 W at 80 K, for 440 We. Further improvement with the inertance tube results in a bottom temperature of 35.1 K and a cooling power of 9.0 W at 77 K, 300 We input power, which is a 10% increase.

Table 2. Dimension of the first-stage PTC

	Regenerator	Pulse tube	Inertance tube 1	Inertance tube 2
Inner Diameter(mm)	26.6	15.0	3.0	5.0
Thickness(mm)	0.4	0.3	1	0.5
Length(mm)	75	75	1370	4100



Figure 3. Cold head of the first stage PTC

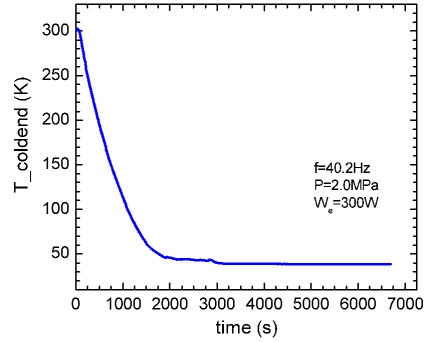


Figure 4. Cooling down time of the first stage

The comparison between experiment result and design model is presented in Figure 5 and Figure 6. The difference is quite small at the typical condition, with an assumption of 50% conversion efficiency between electrical consumption and PV power. So the Carnot efficiency is 17.4% at 77 K, for the improved case, which is almost the same with the object. It is hard to get 15 W at 80 K due to the current limit of the compressor.

THERMAL BRIDGE CALIBRATION

It is easy to measure the precooling temperature, but not the heat lift. We try to measure the precooling heat flow here. Since the thermal bridge is detachable, there is no interference from the second stage during calibration, which is an inherent advantage.

The calibration system is shown in Figure 7. Q_{in} is the simulated heat load, Q_{prec} is the actual precooling heat load if the staged cooler is assembled. The points of T1 and T2 are placed

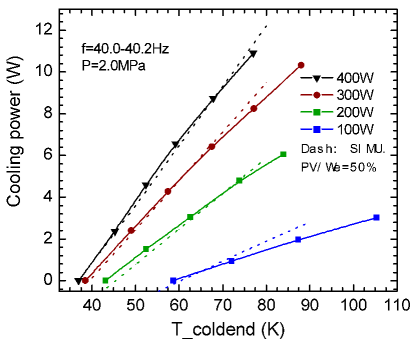


Figure 5. Comparison of simulation and experiment for load lines at different input powers

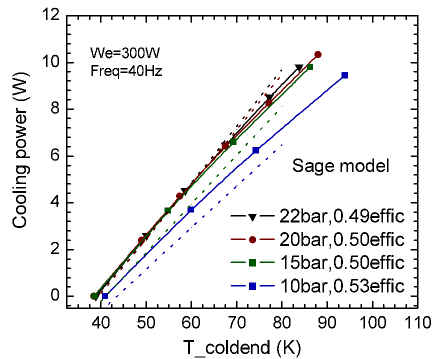


Figure 6. Comparison of simulation and experiment for load lines at different charging pressure

with two PT100 thermometers, one is in the copper block of the first stage, and the other is on the bridge. The width of the thermal bridge is 50 mm, and the height is 10 mm. The distance between the two thermometers is 65 mm. The thermal conductivity of copper is a strong function of temperature and residual resistance ratio (RRR). We choose a typical condition of 100 K and 100, and it is found that the conductivity equals 461 W/(K-m).

Applying the Fourier function $Q=KA_{cr}(\Delta T/L)$, we calculate the heat conduction capacity as $C_{hc}=Q/\Delta T=KA_{cr}/L$. It is easy to get the calculated result, which is 3.55 W/K.

Actually, the contact between thermal bridge and cold heat exchanger of the first stage is not perfect, the geometry is not as simple as a cuboid, and it is not easy to measure the RRR of the copper. So it is necessary to do an experimental calibration.

The linearity of the line indicates a constant conduction capacity of the bridge for various heat flow at temperature range of 75 K to 105 K, as Figure 8 shows. A value of 1.11 W/K shows a significant difference from theoretical calculation.

In this case, once we measure the temperature difference, we know the precooling heat load, which is essential for energy flow analysis.

PRELIMINARY TEST OF THE SECOND STAGE

The second stage is first tested with only inertance tube as phase shifter, as seen in Figure 9. The inertance tube is a two-sectional tube with an inner diameter of 3.0 mm and 4.8 mm, respectively. The second stage is operated at 30 Hz, 1.0 MPa, under the design condition, with an input power of 400 W.

It takes about 90 min to get cooldown to 35 K. After another 4 hours it gets down to a temperature of 20.6 K, as Figure 10 shows, which is quite low for such structure. Meanwhile, the precooling temperature of the first stage is 87.2 K. It is also easy to know the precooling heat load with the calibrated thermal bridge. A temperature difference of 3.3 K means a precooling of 3.7 W.

Figure 11 shows the cooling capacity of the second stage, 1.0 W was achieved with an increase of 8.0 K from the bottom temperature. As the temperature increases, the precooling heat load increased a bit, about 8% in this case.

The simulation result is also shown here, which is quite agreeable with the experiment result, as shown in Figure 11. Comparison data in Table 3 shows that the conversion of the compressor is about 55%, since the compressor is far from resonance. There is one part of power loss cannot be omitted, since the transfer line is longer than one meter. There is only about 150 W of PV power at the inlet of the regenerator.

The performance of the second stage will increase a lot if a double-inlet valve is added¹⁵. In our model, the bottom temperature will decrease about 9 K, and there will be a cooling power of over 1 W at 20 K.

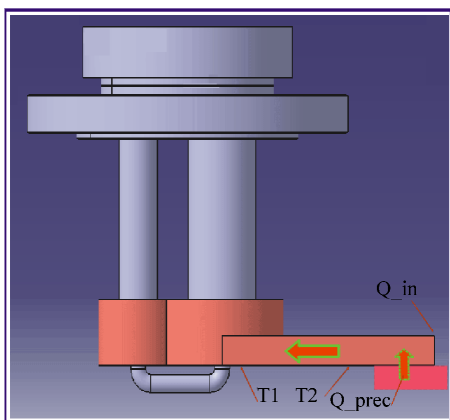


Figure 7. Sketch of thermal bridge calibration system

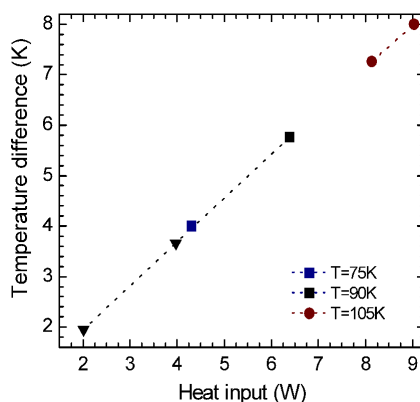


Figure 8. Experiment result of thermal bridge calibration

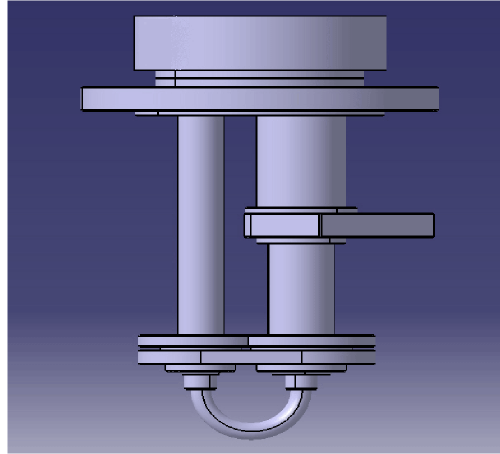


Figure 9. Set-up model of the second stage

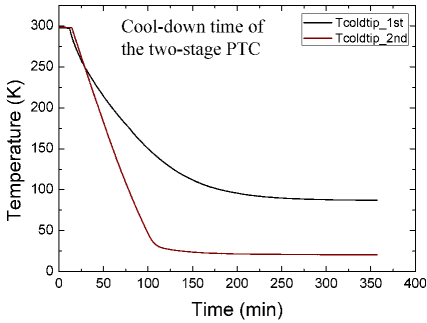


Figure 10. Cooling down time of the two-stage PTC

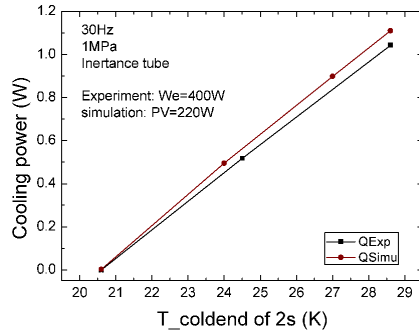


Figure 11. Cooling capacity of the second stage

Table 3. Simulation result for the second stage

	Input Power	T_bottom	Cooling Power
Experiment	400 We	20.6 K	1.0W@28.6K
Simulation	220 W(PV)	20.6 K	1.1W@28.6K

CONCLUSION

A three-stage Stirling PTC of thermal-coupled type is designed, which aims to reach 4 K and investigate the cooling and coupling mechanism for basic research. The experiment test of the first and second stages shows a high performance, which is in good agreement with the thermodynamic model. The verification of the model confirms our ability to achieve our goal finally.

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