Development of a Two-Stage Stirling Type Pulse Tube Cooler with Precooling inside the Pulse Tube

X. Pang[1,2], X. Wang[1], W. Dai[1], E. Luo[1], Y. Zhao[1,2]

[1]Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry of Chinese Academy of Sciences, Beijing 100190, China
[2]Graduate University of Chinese Academy of Sciences, Beijing 100049, China

ABSTRACT

This paper presents the performance of a thermally-coupled two-stage pulse tube cooler. In the cryocooler, an independent 50 Hz Stirling type pulse tube cooler is used to precool the middle of the regenerator as well as the pulse tube of another Stirling type pulse tube cooler with a lower operating frequency. The other cooler forms a configuration referred as a thermally-coupled two-stage configuration. The phase shifter of the first stage is an inertance tube plus reservoir. In order to enhance the performance, a double-inlet orifice is added in the second stage. Theoretical studies and optimization based on Sage® software is first carried out and then experimental apparatus is set up. Experimental results show that with precooling inside the 2nd stage pulse tube, a cooling capacities of 0.73 W at 20 K is obtained, which is more than 2 times as high as the original cooler without precooling (0.27 W). Total electric power input is 540 W (first stage is about 350 W and the second stage is about 190 W). The influence of the pressure ratio, precooling temperature, mean pressure and frequency are also studied.

INTRODUCTION

Refrigerators working at liquid hydrogen temperature are needed for superconductor cooling applications, mid-infrared sensors and space applications. There is an urgent need for efficient coolers with low maintenance and high reliability. Among the different coolers, pulse tube coolers have the advantages of a simple structure, low vibration over traditional regenerative coolers such as Gifford Mcmahon (G-M) and Stirling coolers due to no moving parts in the low temperature region [1]. Stirling-type pulse tube coolers with oil-free compressor are attractive due to their light weight, high reliability and high efficiency [2]. Stirling-type single stage pulse tube coolers at liquid nitrogen temperature [3-4] have been successfully developed and commercialized. For temperature around 20 K, both two stage and single stage configuration have been reported.

L. Yang et al., in 2008 developed a thermally-coupled two stage pulse tube cooler with a double inlet orifice as the phase shifter [5]. A no load temperature of 12.8 K was obtained with 400 W of electric power input. The cooling power at 20 K was about 0.3 W. M. Dietrich et al., developed a gas-coupled two stage Stirling-type pulse tube cooler in 2010 [6], a no load temperature of 13.7 K with a cooling power of 12.9 W at 25 K was achieved at an electrical input power of 4.7 kW. A

Cryocoolers 19, edited by S.D. Miller and R.G. Ross, Jr.

two stage pulse tube cooler with a self-precooled pulse tube was tested by L. Qiu et al., in 2012 [7]. After precooling at near the pulse tube wall, the no load temperature decreased from 26.6 K to 18.02 K. By further optimization, a no load temperature of 15.87 K was reached with 740 W of electrical power input and the cooling power at 20 K was less than 0.2 W. Besides the two stage configuration, there are also some studies of a single stage configuration. L. Chen et al., developed a single stage multi-bypass pulse tube cooler in 2014 [8]. A no-load temperature of 14.7 K was obtained and the maximum cooling power at 20 K was 0.39 W with 250 W electric power input. Q. Zhou et al., further optimized it [9] with a no load temperature of 13.9 K, which is the lowest temperature of a single stage pulse tube cooler ever reported. A further improvement in the efficiency of the Stirling-type pulse tube coolers working within this temperature region is one of the research focuses in this field.

This paper introduces the development of a two-stage Stirling pulse tube cooler which has a thermally-coupled configuration. The configuration provides the ability to study the influence by easily changing components. This serves as the first stage of a project aimed at developing a compact pulse tube cooler system at 20 K. The configuration details and the simulation tool are briefed first, the experimental setup is introduced next, and followed by the presentation of experimental results and discussions last. Finally, some conclusions are drawn.

GEOMETRICAL CONFIGURATION AND NUMERIC MODEL

System configuration

Figure 1 illustrates the system configuration with a coaxial configuration for both stages. Each stage is driven by a compressor respectively. The phase shifter for the first stage is an inertance tube plus reservoir. The double-inlet value is added in the second stage to obtain better performance. Normally, the thermally-coupled two stage pulse tube cooler only has the precooling thermal link at the middle of the 2nd stage regenerator. As shown in Figure 1, the 2nd stage pulse tube is also precooled to improve the cooling performance and is investigated in this paper.

Numeric model and simulation results

For the first stage, we directly use an existing pulse tube cooler in the laboratory and no simulation is required. The parameters of the pulse tube cooler are shown in Table 1.

The second stage cooler is simulated through Sage®[10] software developed by Gedeon Associates, which can simulate and optimize a variety of thermal systems based on an oscillating flow. The geometric parameters are selected according to the numeric calculation results which are shown in Table 2. For Regenerator 21 (RG 21), 300 mesh stainless steel screens with diameter of

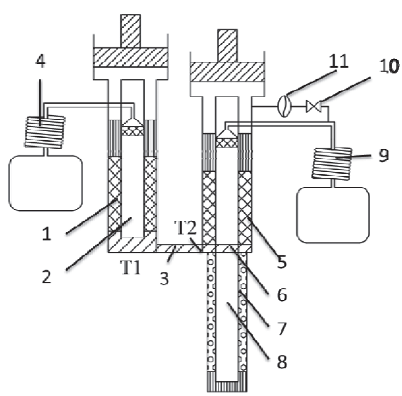

Figure 1. Schematic of the two stage pulse tube cooler: 1 Regenerator 1 (RG 1), 2 Pulse tube 1 (PT 1), 3 Thermal bridge , 4 1st inertance tube, 5 Regenerator 21 (RG 21), 6 Middle heat exchanger, 7 Regenerator 22 (RG 22), 8 Pulse tube 2 (PT 2), 9 2nd inertance tube, 10 double-inlet value, 11 membrane.

Table 1. Geometric parameters of the first stage pulse tube cooler

Component	Parameters（mm）（Diameter*Length）
RG 1	Φ25*45
PT 1	Φ12.8*64
1st inertance tube	Φ3*3.4

30 μm are used as the matrix material. HoCu2 spheres with diameter of around 0.2 mm are used in Regenerator 22 (RG 22).

Figure 2 shows the influence of a double-inlet orifice on the system performance with a constant acoustic power input of 130 W. With only a inertance tube plus reservoir as the phase shifter, the system cannot obtain the desired performance and the no load temperature only reaches 31 K. The double-inlet orifice improves the phase difference between the pressure wave and the volume flow rate at the hot end of the pulse tube which is helpful for obtaining better cooling performance. However, the simulation results show that decreasing the no-load temperature is not a sole function of the phase difference. With increasing the openings of the double-inlet, the phase difference also increases, but there is a minimum no load temperature corresponding to the optimum double-inlet opening.

EXPERIMENTAL SETUP

Based on the numerical simulations, a two-stage pulse tube cooler has been developed with parameters shown in Table 1 and Table 2. Figure 3 shows the photo of the cold head. A middle heat exchanger is set inside the 2nd stage pulse tube, which is also precooled by the cold tip of the first stage (see Figure 1). The thermal bridge, which connects the first stage cooler and the second stage cooler, is composed of 0.1 mm thick copper plates with bends to provide flexibility. The corresponding overall length, width and height is about 155 mm × 70 mm × 10 mm. A copper radiation shield, which is thermally attached to the thermal bridge, surrounds the low temperature part of the second stage. In order to further reduce the radiation losses, aluminized foil is wrapped around the two stages and the copper shield.

Table 2. Geometric parameters of the second stage pulse tube cooler

Component	Parameters（mm）（Diameter*Length）
RG 21	Φ25*35
RG 22	Φ18.8*65
PT 2	Φ10*154.5

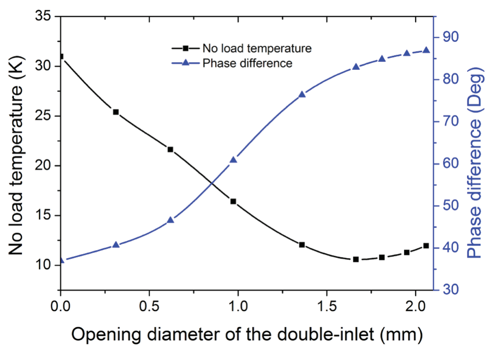

Figure 2. Influence of the double-inlet on system performance, 130 W acoustic power input

Figure 3. Photo of the two stage cold head

The cold head of each stage is driven by a linear compressor respectively of the moving-magnet type. A dual-opposed motor configuration is used to ensure then easy cancellation of vibration. The pressure waves are measured by dynamic pressure transducers (113B21, PCB piezotronics Inc.) which are placed at the compression chamber and the backside chamber of the compressors. Two platinum resistance thermometers (PT 100) with an accuracy of ± 0.1 K are attached to the heat exchanger to measure the temperature of T1 and T2 (show in Figure 1). A calibrated resistance thermometer (LakeShore) with 0.01 K accuracy is used to measure the temperature of T3 (2nd stage cold end). Cooling power is measured through a heating wire which is mounted on the cold end heat exchanger and powered by a DC voltage source.

EXPERIMENTAL RESULTS AND DISCUSSIONS

Cooling performance

During the experiments, the first stage is working at 50 Hz and 3.5 MPa. The second stage is working at 30 Hz and 2.5 MPa, if not specially mentioned. The cool down curves are given in Figure 4. Compared with the cooler with non-precooled pulse tube, the system with precooling inside the middle of pulse tube obtains a better cooling performance. No load temperature decreases from 18.86 K to 15.35 K. The cooling power at 20 K is more than 2 times higher than with the non-precooled pulse tube (0.73 W vs. 0.27 W), which shows the effectiveness of the middle heat exchanger inside the 2nd stage pulse tube. The electric power input is about 540 W (first stage about

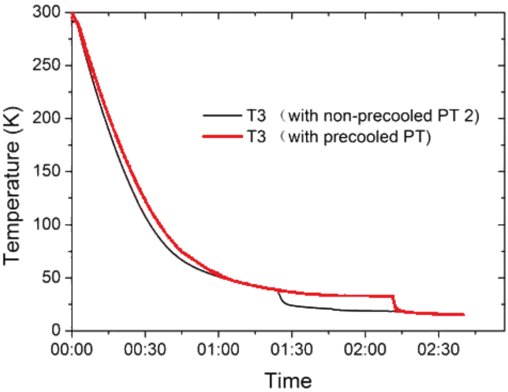

Figure 4. Cooling down process of the system

350 W and the second stage about 190 W). The following studies focus on the pulse tube cooler with precooling inside the middle of the 2nd stage pulse tube.

Influence of important parameters

The inertance tube affects the cooling performance. Figure 5 shows the no load temperature with different lengths of the inertance tube (optimized opening of the double-inlet). The acoustic power is approximately the same during the experiments, about 130 W. There is an optimum length (around 3.3 m) for the inertance tube to obtain a minimum no load temperature.

In addition to the phase shifter, the influence of the pressure ratio, the precooling temperature and the mean pressure are also investigated. Figure 6 shows the effect of the pressure ratio. The maximum value is about 1.22 due to the limitations of the piston displacement. The optimized no load temperature is about 15.35 K. From the trend of the curve, if the pressure ratio can be improved, the performance will be better.

As shown in Figure 7, the no load temperature changes almost linearly with the precooling temperature with approximately 130 W acoustic power input. Due to the limited cooling capacity of the first stage, the minimum precooling temperature is about 76 K. With a precooling temperature increase of 5.5 K, the no load temperature increases by about 1 K.

The operating frequency is also an important parameters. The effect of the frequency is shown in Figure 8. With the frequency changing from 28 Hz to 32 Hz, the change in no load temperature

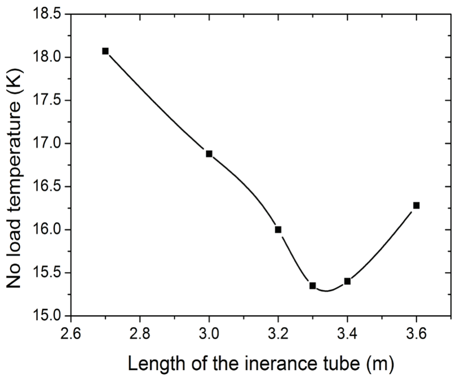

Figure 5. No load temperature vs. length of the inertance tube

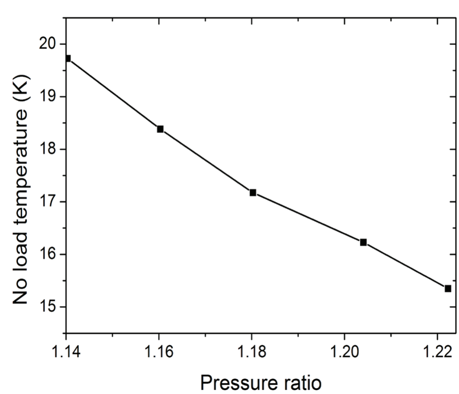

Figure 6. No load temperature vs. pressure ratio

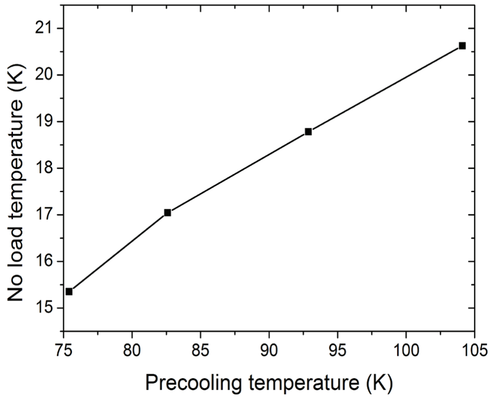

Figure 7. No load temperature vs. precooling temperature

is less than 1 K. The optimized operating frequency is about 30.5 Hz, which is very close to the designed frequency (30 Hz). Figure 8 also indicates that when the operating frequency is close to the optimized value, the effect on the no load temperature is small.

The relationship between the filling pressure and cooling performance is given in Figure 9. In the experiments, the maximum acoustic power input is different with different filling pressures. Considering the limitations of the compressor piston displacement, the swept volume of the compressor is kept the same for the experiments with different filling pressure. As shown in Figure 9, the no load temperature is nearly the same with four different filling pressures. However, with a higher filling pressure, the cooling power at 20 K is higher. A cooling power of 0.94 W at 20 K is obtained with 3.3 MPa mean pressure.

CONCLUSION

A thermally-coupled two stage pulse tube cooler with precooling inside the second stage pulse tube has been developed and tested. A no-load temperature of 15.35 K and cooling capacities of 0.73 W at 20 K are obtained with 540 W electric power input (first stage about 350 W and the second stage about 190 W). The cooling performance is much better than that with non-precooled pulse

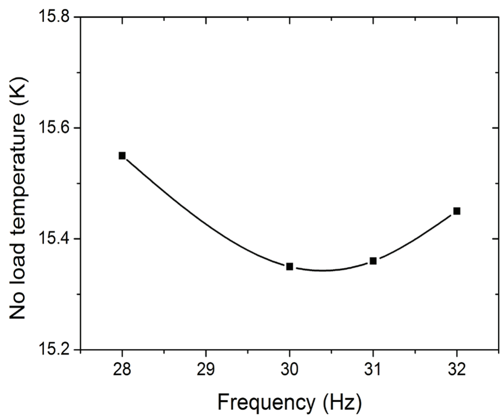

Figure 8. No load temperature vs. frequency

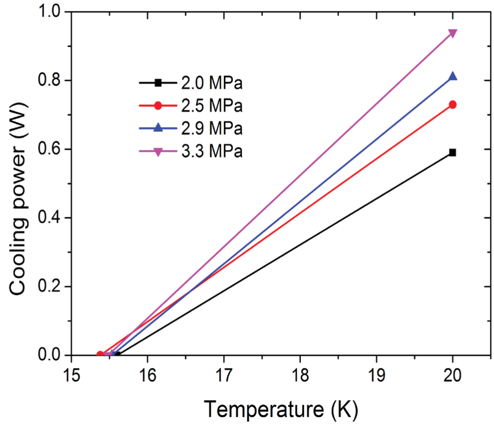

Figure 9. Cooling power vs. temperature

tube. The study reveals that the system can obtain a better performance with higher pressure ratio and lower precooling temperature. Through increasing the filling pressure, a cooling power of 0.94 W has been obtained under 3.3 MPa.

ACKNOWLEDGMENT

This work is financially supported by the National Natural Science Foundation of China (Contract number 51376187, 51576205) .

REFERENCES

1. Radebaugh, R., "The development and application of cryocoolers since 1985," *Proceedings of ICCR* 2003, International Academic Publishers/Beijing World Publishing Corporation (2003), pp. 858-70.
2. Radebaugh, R., "Development of the pulse tube refrigerator as an efficient and reliable cooler," *Proc. Institute of Refrigeration*, London, vol. 96 . 1999-2000; 11-31.
3. Hu, J.Y., Zhang, L.M., Zhu, J., Chen, S., Luo, E.C., Dai, W. and Li, H.B., "A high-efficiency coaxial pulse tube cryocooler with 500W cooling capacity at 80K," *Cryogenics*, Vol. 62(2014), pp. 7-10
4. Wang, X., Dai, W., Hu, J., Luo, E. and Zhou, Y., "Performance of a Stirling-Type Pulse Tube Cooler for High Efficiency Operation at 100Hz," *Cryocoolers 16*, ICC Press, Boulder, CO (2011).
5. Yang, L., "Investigation on a thermal-coupled two-stage Stirling-type pulse tube cryocooler," *Cryogenics*, vol. 48 (2008), pp. 492-496.
6. Dietrich, M. and Thummes, G., "Two-stage high frequency pulse tube cooler for refrigeration at 25 K," *Cryogenics*, vol. 50 (2010), pp. 281-286
7. Qiu, L.M., Zhi, X.Q., Han, L., Cao, Q. and Gan, Z.H., "Performance improvement of multi-stage pulse tube cryocoolers with a self-precooled pulse tube," *Cryogenics*, vol. 52 (2012), pp. 575-579.
8. Chen L, Zhou Q, Zhu X, et al., "Lightweight Stirling-type pulse tube cryocooler with temperature below 20 K," *Journal of Engineering Thermophysics*, vol. 35(5) (2014), pp. 858-861.
9. Zhou, Q., Chen, L., Zhu, X., Zhu, W., Zhou, Y. and Wang, J., "Development of a high-frequency coaxial multi-bypass pulse tube refrigerator below 14 K," *Cryogenics*, vol. 67 (2015), pp.28-30.
10. Gedeon, D., "Sage User's Guide," Gedeon Associates, Athens, OH, (2009).