Design and optimization of a 20 K small length-diameter ratio thermal-coupled two-stage pulse tube cryocooler

Bin Yang[1.2.3], Chenglong Liu[1.2.3], Mingtao Pan[1.2.3], Bo Tian[1.2.3], Jia Quan[1.2*], Yuexue Ma[1.2], Yanjie Liu[1.2], Houlei Chen[1.2], Miguang Zhao[1.2], Jingtao Liang[1.2.3]

[1] Technical Institute of Physics and Chemistry, Chinese Academy of Science, Beijing, China
[2] State Key Laboratory of Cryogenic Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
[3] University of Chinese Academy of Sciences, Beijing, China

[*]E-mail: quanjia10@mail.ipc.ac.cn

Abstract. The suitable cryogenic environment is a necessary condition for ensuring the high precision and high sensitivity operation of space exploration equipment. The two-stage pulse tube cryocooler (PTC) is the basis for the normal operation of space exploration equipment working in the liquid hydrogen temperature range and cryogenic systems such as the Joule-Thomson cryocooler that requires pre-cooling in the liquid hydrogen temperature range. Currently, the 2nd-stage regenerator length-diameter ratio of most two-stage PTC are greater than 2.5. However, for occasions with high structural strength requirements and thermal coupling with large-area array detectors, small length-diameter ratio PTCs will be preferred. Therefore, a small length-diameter ratio thermal-coupled two-stage PTC was designed in this study, and experimental optimizations were conducted on the 2nd-stage inertance tube and double-inlet. After optimization, the lowest no-load cooling temperature of 11.75 K was obtained. With a total electric power of 290 W, a cooling capacity of 784 mW@20 K was obtained, resulting in a maximum relative Carnot efficiency (rCOP) of 4.36 %.

1. Introduction

In recent years, the accelerated advancement of deep-space exploration technologies and quantum technologies has driven the deployment of diverse spaceborne instrumentation aboard spacecraft. A precisely controlled cryogenic environment constitutes an essential prerequisite for sustaining the high-precision and high-sensitivity operational performance of such space exploration equipment.[1]. The pulse tube cryocooler (PTC) is widely used in the pre-cooling of space exploration equipment because of its simple structure, high reliability, low vibration, long life, and no moving parts of the cold head. In the past few decades, significant efforts have been made to develop PTCs capable of providing the cryogenic environments required by various space exploration equipment. For instance, infrared detection equipment working in the liquid nitrogen temperature range of generally uses a single-stage PTC for pre-cooling. Long-wave infrared detectors and electrically substituted absolute radiometers[2] working in the liquid hydrogen temperature range generally uses two-stage PTC. Space

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

equipment such as terahertz detectors and microcalorimeters, which work in both the liquid helium and millikelvin temperature ranges, require cryogenic environments provided by the Joule-Thomson cryocoolers[3], adiabatic demagnetization refrigerators[4], or dilution refrigerators[5]. These cryocooler systems often also necessitate two-stage PTCs as pre-cooling units. Therefore, the PTC technology is a crucial foundation for the development of space technology.

The cold finger structure of the PTC varies with different application scenarios. For applications with small volume and light weight, small lengths and small diameters PTCs are preferred. And for occasions with high structural strength requirements and thermal coupling with large-area array detectors[6,7], large diameter and small length-diameter ratio will be preferred. This is because, firstly, the large structural strength of the small length-diameter ratio PTC itself is expected to reduce or even replace the adiabatic support column of the large-area array detector cold platform, resulting in a more simplified structure. Secondly, the contact area between the cold head of the small length-diameter ratio PTC and the large-area array cold platform is larger, which results in more efficient heat transfer from the cold head to the large-area array cold platform. In addition, small length-diameter ratio PTC (more precisely, large-diameter PTCs) have a greater upper limit in cooling performance potential when coupled with larger sweep volume compressors.

At present, the diameter of single-stage PTCs varies greatly depending on the application requirements, as shown in Table 1. Most of the studies focusing on two-stage PTCs have a length-diameter ratio of greater than 2.5, as shown in Table 1. A small length-diameter ratio PTC was designed, experimentally optimized and performance tested in this study.

Table 1. Research on single-stage and two-stage PTC

	Year	R&D institutions	Researcher	Structure	Cooling capacity	Cold finger diameter
Liquid nitrogen temperature range	2018	TIPC, CAS[8]	Wang.	single-stage	13W@80K	28mm
	2023	TIPC, CAS[9]	Zhang.	single-stage	100W@90K	70mm
	2024	TIPC, CAS[10]	Li.	single-stage	12.7W@60K	30mm
Liquid hydrogen temperature range	2021	TIPC, CAS[11]	Zhu.	two-stage	0.67 W@20 K	13.7mm
	2021	SITP, CAS[12]	Wu.	two-stage	0.83 W@20 K	19.4mm
	2022	SITP, CAS[13]	Jiang.	two-stage	1.15 W@20 K	20mm
	2023	TIPC, CAS[14]	Gao.	two-stage	0.54W@20K	18.9mm
	2023	SITP, CAS[15]	Wang.	two-stage	1.87 W@20 K	21.5mm
	2023	TIPC, CAS[16]	Yang.	two-stage	0.94 W@20 K	21.5mm

2. Design of 2nd-stage PTC

The 2nd-stage regenerator, 2nd-stage pulse tube, and pre-regenerator are key components of the PTC, and their diameters, lengths, and thicknesses have significant effects on the cooling capacity, rCOP and other performance parameters of the entire system. In the following, Sage is used to simulate, which is a one-dimensional numerical simulation software developed based on computational fluid dynamics[17] and suitable for the simulation and optimization of PTCs. A comparison will be made through simulations of the cooling capacity and rCOP of the 2nd-stage

regenerator and 2nd-stage pulse tube at different diameters to determine the optimal diameter. While the cooling capacity can be directly calculated using Sage, rCOP needs to be derived through calculations. rCOP can be expressed as:

$$\mathrm{r}COP=\frac{\zeta_1}{\zeta_2}\times 100\% \tag{1}$$

Where ζ_1 and ζ_2 represent the actual refrigeration coefficient and the reverse Carnot cycle refrigeration coefficient, respectively, they can be expressed as:

$$\zeta_1=\frac{Q_c}{W_1+W_2} \tag{2}$$

$$\zeta_2=\frac{T_c}{T_h-T_c} \tag{3}$$

Where Q_c is the 2nd-stage cooling capacity, W_1 and W_2 are 1st-stage and 2nd-stage input powers respectively, T_c is the 2nd-stage cold-end temperature, and T_h is the 2nd-stage hot-end temperature, set at 300K. W_1 can be calculated equivalently based on the pre-cooling capacity of the thermal bridge in the model. Currently, rCOP of a single-stage PTC with inertance tube and reservoir as the phase shifter at 80K is approximately 20% [18-20], with a power consumption to cooling capacity ratio of 13.75/1 at 80K. Therefore, *W1* can be expressed as:

$$W_1=13.75Q_1 \tag{4}$$

Where Q_1 is the 1st-stage pre-cooling capacity, which can be directly obtained from the model. Combining equations (1) to (4), rCOP of 2nd-stage PTC can be expressed as:

$$\mathrm{r}COP=\frac{(300-T_c)Q_c}{T_c(13.75Q_1+W_2)}\times 100\% \tag{5}$$

According to the application requirements, the inner diameter of a two-stage pulse tube is estimated first. In this case, 18.2mm is selected and input into the sage. The simulation results of the cooling capacity at 20 K, rCOP, and pre-cooling capacity at 80 K as the inner diameter of the 2nd-stage regenerator varies are shown in Figure 1. The results indicate that the optimal inner diameter of the 2nd-stage regenerator is 35 mm. At this time, the length-diameter ratio of the 2nd-stage regenerator is 1.56. Figure 2 displays the simulation results of the cooling capacity at 20 K, rCOP, and pre-cooling capacity at 80 K as the inner diameter of the 2nd-stage pulse tube varies, with the inner diameter of 2nd-stage regenerator fixed at 35mm. The results reveal that the optimal inner diameter of the 2nd-stage pulse tube is 17.8mm. At this time, the length-diameter ratio of the 2nd-stage pulse tube is 2.83. The diameter of the pre-regenerator is generally a little larger than that of the 2nd-stage regenerator, so its inner diameter was chosen as 40 mm. Due to the increased weight of the entire system, there is a higher demand for the load-bearing strength of the cold finger, and the larger cold finger diameter may lead to deformations during machining and welding processes. Therefore, the thickness of the 2nd-stage pulse tube, 2nd-stage regenerator, and pre-regenerator are all increased to 0.3mm each. After optimization of 2nd-stage regenerator and pulse tube, it can be seen from Figure 2 that a cooling capacity of 813.6 mW@20 K can be obtained. In summary, a set of optimal diameters for 2nd-stage cold finger were determined, with specific dimensions and increased multipliers in the cross-sectional area are shown in Table 2.

Table 2. Research on single-stage and two-stage PTC

Component	Inner diameter	Thicknesses
2nd-stage pulse tube	17.8mm	0.3mm
2nd-stage regenerator	35mm	0.3mm
Pre-regenerator	40mm	0.3mm

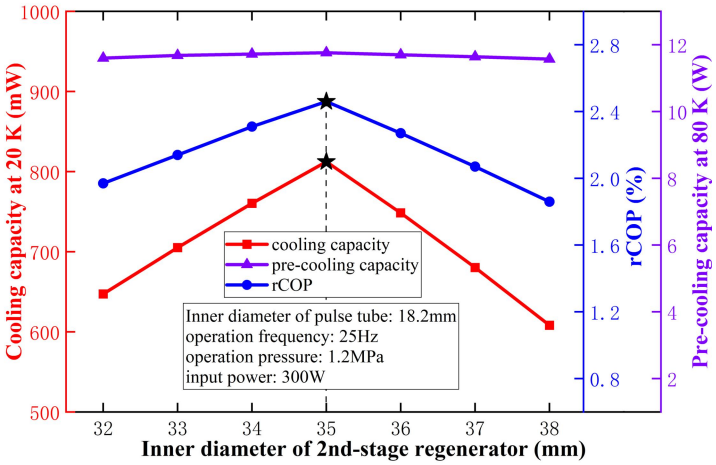

Figure 1. Cooling performance with diameter of the 2nd-stage regenerator

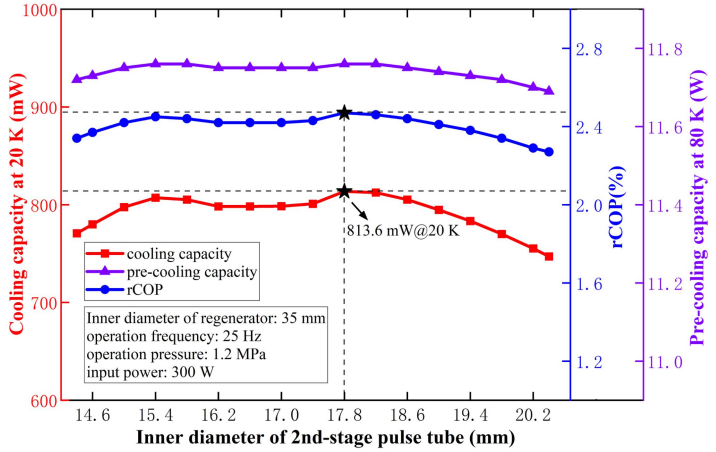

Figure 2. Cooling performance with diameter of the 2nd-stage pulse tube

3. Optimization of 2nd-stage inertance tube

The phase shifter, as a key component influencing the performance of the PTC, primarily provides the appropriate impedance to the hot-end of the pulse tube to optimize the performance of the PTC. The inertance tube, serving as the core component of the phase shifter, has the most significant impact on the performance of the PTC and therefore requires optimization. The optimal inertance tube combination varies with different cold finger. Therefore, the 2nd-stage inertance tube needs to be optimized.

Using Sage to simulate the cooling capacity at 20 K of the PTC with different inertance tube combinations in Table 3 at a 2nd-stage operation pressure of 1.2 MPa, the simulation results are illustrated in Figure 3, with each case operating at its optimal frequency. Simulation results

indicate that from case 1 to case 6, the cooling capacity at 20 K gradually decreases, suggesting that the 2nd-stage cold finger is more compatible with inertance tube combinations of higher resistance. Additionally, from case 1 to case 6, the optimal frequency gradually increases due to the shorter length and thicker diameter of the inertance tube combinations, leading to a decrease in resistance.

Table 3. Inertance tube combination methods

Case	Inertance Tube Combination Methods
1	Φ2mm×1.5m+Φ3mm×2m+Φ4mm×2m
2	Φ3mm×2m+Φ4mm×2m
3	Φ4mm×2m+Φ5mm×2m
4	Φ4mm×2m+Φ5mm×1m
5	Φ4mm×1m+Φ5mm×2m
6	Φ4mm×1m+Φ5mm×1m

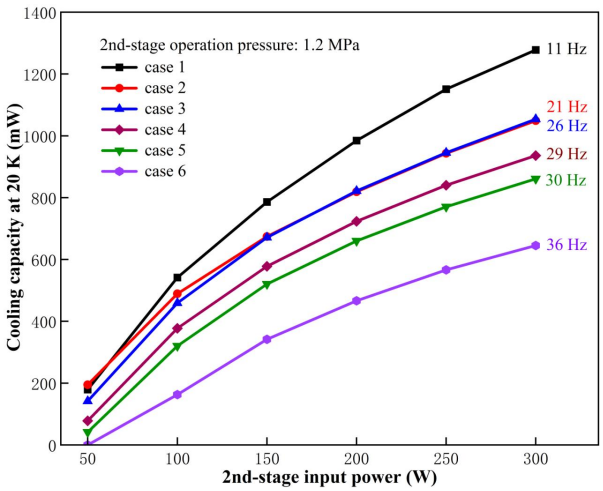

Figure 3. Cooling performance with diameter of the 2nd-stage pulse tube

Based on the above optimization results, the small length-diameter ratio thermal-coupled two-stage PTC was processed. Experimental studies were then conducted on case 1, 2, and 3, which exhibit the highest cooling capacities at 20 K in simulation. To compare the differences in cooling performance among 3 cases, Figure 4 illustrates the comparison of cooling capacity at 20 K and rCOP at a 2nd-stage operation pressure of 1.1 MPa and a 2nd-stage electrical power of 220 W. The specific operating parameters are detailed in Table 4. The experiments revealed that the cooling capacity at 20 K and rCOP were the lowest when the small length-diameter ratio PTC coupling case 1. This indicates that case 2 and case 3 are more suitable for the 2nd-stage cold finger of small length-diameter ratio two-stage PTC.

Table 4. Specific operating parameters

Operation pressure	Electrical power	Cooling capacity at 20K		
		case 1	case 2	case 3
1.1MPa	220W	509mW	720mW	671mW

4. Optimization of double-inlet

The double-inlet, as an essential component of the phase shifter, operates on the principle that a portion of the gas directly enters the pulse tube hot-end without passing through the 2nd-stage regenerator. This not only reduces the heat load on the 2nd-stage regenerator but also the gas introduced through the double-inlet can effectively suppress the phenomenon that the mass flow is ahead of the pressure wave at the pulse tube hot-end. The phase shifting capability is determined by double-inlet orifice diameter determines. Therefore, experimental tests were conducted by installing double-inlet with 0 mm and 0.28 mm aperture on the small length-diameter ratio PTC, with the results shown in Figure 4. When coupling double-inlet with 0 mm aperture with the PTC, the no-load cooling temperature is lower, and the cooling capacity at 20 K is larger. The lowest no-load cooling temperature of 11.75K was achieved at a 2nd-stage input power of 100W. With a total electric power of 290 W, a cooling capacity of 784 mW@20 K was obtained, resulting in a maximum rCOP of 4.36 %.

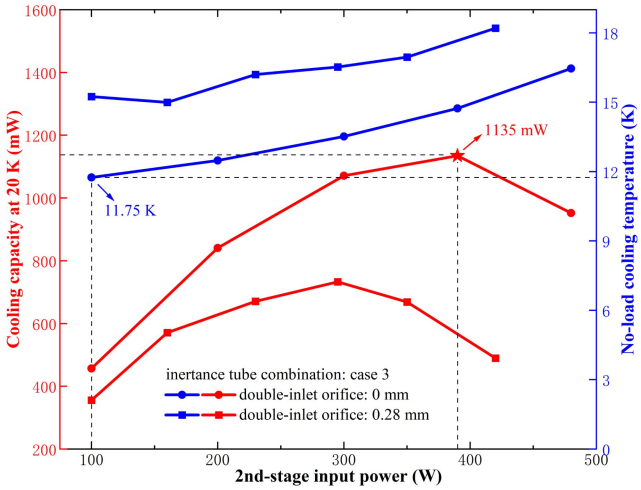

Figure 4. Comparison of cooling capacity at 20K and no-load cooling temperature of different double-inlet

5. Conclusion

A small length-diameter ratio thermal-coupled two-stage PTC was designed and experimental optimization was conducted on the 2nd-stage inertance tube and double-inlet of the small length-diameter ratio PTC. The optimization resulted in the lowest no-load cooling temperature of 11.75 K. Under a total electric power of 670 W, a cooling capacity of 1135 mW@20 K was achieved. With a total electric power of 290 W, a cooling capacity of 784 mW@20 K was obtained, resulting in a maximum rCOP of 4.36 %.

Acknowledgments

This work is supported by the Innovation Program for Quantum Science and Technology (No. 2023ZD0300100)

References

[1] ROSS R G. Aerospace Coolers: A 50-Year Quest for Long-Life Cryogenic Cooling in Space [M]//TIMMERHAUS K D, REED R P. Cryogenic Engineering. New York, NY; Springer New York. 2007: 225-84.

[2] Yi XL, Ye X, Fang W, et al. Prospects for the application of electric substitution absolute radiometers and earth radiation detection (in Chinese) [C]. The 9th Academic conference of the Geophysical Technical

Committee of the Chinese Geophysical Society - abstract collection of the symposium on global geophysical exploration and intelligent perception, F, 2021.
[3] Liu ZY, Yang B, Pan ZJ, et al. The thermal performance model of a 105 mW@4.41 K 4He Joule-Thomson cryocooler designed for space applications[J]. Cryogenics, 144(2024)103965.
[4] Zhao SB, Quan J, Yang B,et al. Cooling system for DIXE mission from 300 K to 4 K[J]. Cryogenics, 150(2025)104135.
[5] Pan ZJ, Zhen MW, Wei LJ, et al. Theoretical analysis of the heat exchanger of a dilution refrigerator for space applications [J]. Cryogenics, 130(2023)103645.
[6] Huang Y, Lu YD, Zhang K, et al. Simulation design and experiment of cold platform for large-area array infrared detector (in Chinese) [J]. Vacuum & cryogenics, 2021, 27(04): 372-377.
[7] He JH, Zhu JB, Zhuang CP, et al. Simulation design and experiment of thermal coupling structure between large-area array detector and Stirling cryocooler (in Chinese) [J]. Vacuum & cryogenics, 2022, 28(02): 164-169.
[8] Wang NL, Zhao MG, Chen HL, et al. Simulation design and experimental verification of a 13 W@80 K space large cooling capacity pulse tube cryocooler (in Chinese) [J]. Journal of mechanical engineering, 2018.
[9] Zhang YT, Wang NL, Zhao MG, et al. Experimental study of regenerator circumferential temperature distribution of large cooling capacity coaxial pulse tube cryocooler (in Chinese) [J]. Cryogenic engineering, 2023.
[10] Li YE, Wang NL, Zhao MG, et al. Numerical and experimental investigation of 12 W/60 K high-efficiency coaxial pulse tube cryocooler. [J]. Cryogenics, 2024.
[11] Zhu QL. Research on multi-stage high-efficiency pulse tube cryocooler in 20K temperature range (in Chinese) [D]. Technical Institute of Physics and Chemistry CAS, 2021.
[12] Wu W., Cui X., Liu S., et al. Cooling performance improvement of a two-stage pulse tube cryocooler with Er-plated screen as regenerative material[J]. International Journal of Refrigeration, 2021(131): 615-622.
[13] Jiang ZH, Song JT, Liu SS, et al. Influence of frequency and pressure on entropy production characteristics of regenerator at 20 K pulse tube cryocooler[J]. International Journal of Refrigeration, 2022, 144: 222-230.
[14] Gao M, Yang B, Li GY, et al. Experimental study on the optimization of two-stage thermal-coupled pulse tube cryocooler regenerator in the 20K temperature range (in Chinese) [C]. The 16th National Conference on Cryogenic Engineering, 2023.
[15] Wang Y, Hui HJ, Wu WT, et al. A 910mW@15K thermal-coupled pulse tube cryocooler with active phase shifter [J]. Journal of Zhejiang University, 2023.
[16] Yang B, Gao M, Quan J, et al. Experimental study on the operating parameters of thermal-coupled two-stage high-frequency pulse tube cryocooler in the liquid hydrogen temperature range (in Chinese) [C]. The 16th National Conference on Cryogenic Engineering, 2023.
[17] D. Gedeon. SAGE User's Guide[M]. 2013.
[18] Zhang Y, Ni ZQ, Luo GQ, et al. 15W@80K research and development of all-gas bearing room temperature piston pulse tube cryocooler (in Chinese) [J]. Cryogenic engineering, 2024, (04):47-56.
[19] Wang XT, Zhang YB, Li HB, et al. A high efficiency hybrid Stirling-pulse tube cryocooler[J]. AIP Advanced 5, 037127, 2015.
[20] Li XW, Dai W, Zhang W, et al. A high-efficiency free-piston Stirling cooler with 350 W cooling capacity at 80K[J]. Energy Procedia, 158(2019)4416-4422.