

Advances in single- and multi-stage Stirling-type pulse tube cryocoolers for space applications in NLIP/SITP/CAS

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Abstract. This paper presents a review of recent advances in single- and multi-stage Stirling-type pulse tube cryocoolers (SPTCs) for space applications developed at the National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences (NLIP/SITP/CAS). A variety of single-stage SPTCs operating at 25–150 K have been developed, including several mid-sized ones operating at 80–110 K. Significant progress has been achieved in coolers operating at 30–40 K which use common stainless steel meshes as regenerator matrices. Another important advance is the micro SPTCs with an overall mass of 300–800 g operating at high frequencies varying from 100 Hz to 400 Hz. The main purpose of developing two-stage SPTCs is to simultaneously acquire cooling capacities at both stages, obviating the need for auxiliary precooling in various applications. The three-stage SPTCs are developed mainly for applications at around 10 K, which are also used for precooling the J-T coolers to achieve further lower temperatures. The four-stage SPTCs are developed to directly achieve the liquid helium temperature for cooling space low-T_c superconducting devices and for the deep space exploration as well. Several typical development programs are described and an overview of the cooler performances is presented.

1. Introduction

Recently, single- and multi-stage Stirling-type pulse tube cryocoolers (SPTCs) have been developed at the National Laboratory for Infrared Physics, Shanghai Institute of Technical Physics, Chinese Academy of Sciences (NLIP/SITP/CAS). This paper presents a review of the capabilities of single-, two-, three-, and four- stage SPTCs including the high performance linear compressors developed for them. Several typical development programs are described and an overview of the cooler performances is provided.



2. Single-stage SPTCS

A series of single-stage coaxial and in-line high efficiency SPTCs have been developed for a variety of space missions. The single-stage SPTCs covering 25–150 K are becoming mature, especially the mid-sized ones operating at higher temperatures such as 80–110 K, several of which have already been flown in space. At the same time, significant progress has been achieved in mid-sized coolers working at 30–40, as well as micro coolers operating at high frequencies varying from 100 Hz to 400 Hz.

2.1. 80–110 K Flight-qualified Mid-size Single-stage SPTC

The single-stage mid-size PTCs operating at 80–100 K have been developed mainly for providing appropriate cooling powers for the middle-scale HgCdTe-based infrared FPAs with short and medium wavelengths, respectively. In order to achieve the desired high efficiencies, systematic optimizations on the phase shifting mechanism and selections of the appropriate operating parameters have been performed. Two types of coolers with typical cooling capacities of 2.0 W at 80 K and 6.0 W at 90 K are shown in TABLE 1, in which 17.8% and 19.2% of Carnot efficiency at 80 K could be achieved for coaxial and in-line prototypes, respectively [1–10]. Based on the above two types, several single-stage SPTCs with high efficiency and long life expectation have already been launched in space, which have the expected Mean-Time-To-Failure (MTTF) of more than 61,000 hours, or seven years.

Table 1. Performance characteristics of two typical types of 80–110 K mid-size single-stage SPTCs.

	MSS-9060	MSS-8020
Working temperature range (K)	80–110	80–110
Typical cooling capacity	6 W@90 K	2 W@80 K
Reject temperature (K)	300 K	300 K
Relative Carnot efficiency at 80 K	17.8% for coaxial type 19.2% for in-line type	17.8% for coaxial type 19.2% for in-line type
Ambient temperature adaptability (K)	238–328	238–328
Overall mass of SPTC (kg)	10.0	5.7
Compressor mass (kg)	7.5	4.2
Operating frequency range (Hz)	45–60	45–60
Expected MTTF (h)	≥61,000	≥61,000

2.2. 30–35 K Single-stage SPTC without neither either double-inlet or multi-bypass

The development of SPTCs operating at 30–35 K has mainly targeted cooling HgCdTe-based infrared detectors with very- long-wavelengths ($>13\ \mu\text{m}$), and GaAs/AlGaAs Quantum-Well infrared photo-detectors (QWIPs) ($>14\ \mu\text{m}$). These SPTCs employ neither double-inlet nor multi-bypass but use the inertance tubes as the only phase-shifter. The above characteristics eliminate the possible DC effect around the closed loop formed by regenerator and pulse tube and thus significantly enhance the stability of the cooling performance. However, the simpler cooler is more difficult to design and optimize. Another significant feature of the development is that, excluding any magnetic or rare earth material, only the conventional stainless steel (SS) mesh is used as the regenerator matrix, which greatly facilitates its practical applications [11–12]. Figure 1 shows the 30–35K single-stage SPTC and the experimental set-up.

One of the main technological innovations is to adopt the mixed regenerator, which consists of three segments filled with different meshes of stainless steel screens, respectively, in order to enhance the regenerator performance at the coldest end and also to minimize the overall flowing resistance along the tube. A two dimensional axis-symmetric CFD model with the thermal non-equilibrium mode has been developed to simulate the internal process and the underlying mechanism of significantly reducing the regenerator losses with mixed matrices studied in detail based on several actual cases. The modeling is used to determine the combination of the given different mesh segments that optimizes the cooling efficiency or the exergy ratio. The experimental units have achieved a no-load temperature of 27.2 K and a

cooling power of 0.29 W at 30 K with an input power of 220 W at a reject temperature of 300 K. Using a two-dimensional regenerator model based on Brinkman-Forchheimer equations, the different filling proportions of mixed matrices made of SS screens are simulated and compared and then the optimal proportion is suggested. The experiments show that the cooling performance can be enhanced further, yielding a no-load temperature of 26.7 K and cooling capacity of 0.45W at 30 K under the same conditions. Figure 2 shows the typical cool-down curve, and the typical simulated and experimental results [11–12].

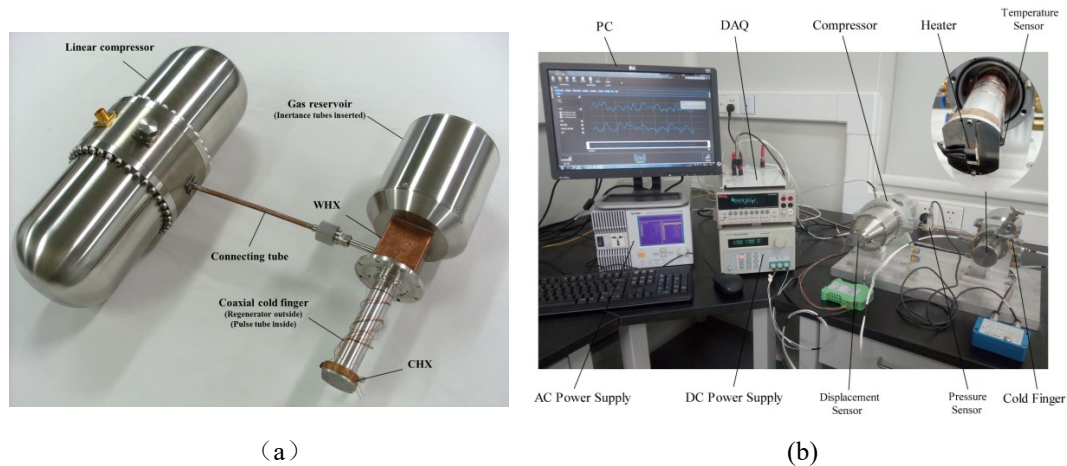


Figure 1. (a) 30-35K Single-stage SPTC; (b) Experimental set-up

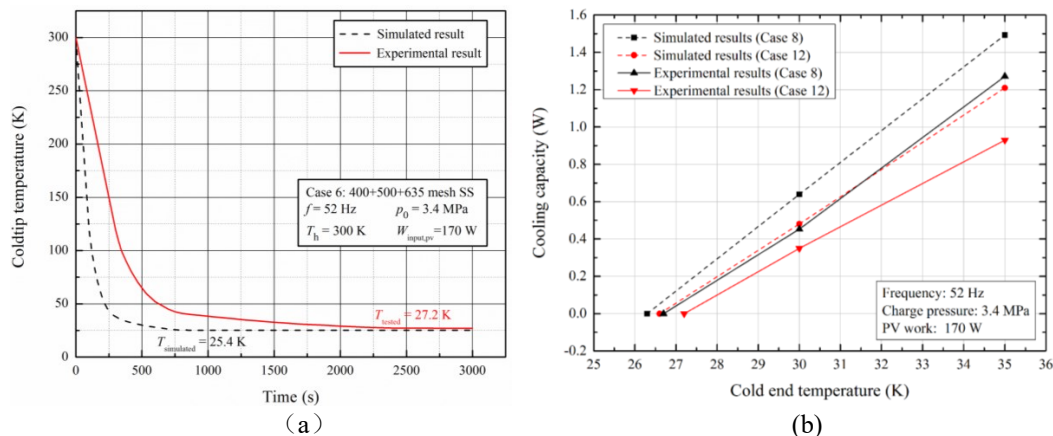


Figure 2. (a) Typical cool-down curve; (b) Typical simulated and experimental results

2.3. Micro coaxial SPTCs operating at very high frequencies

Another important advance in the single-stage SPTCs is the modeling and experimental verifications of some micro SPTCs with an overall mass of 300–800 g operating at very high frequencies varying from 120 Hz up to 400 Hz, which have important potential applications in both space and aeronautics fields.

Miniaturization of coolers for low-temperature applications has attracted worldwide attention. Many of these applications are based on optical and electronic technologies and only require relatively small cooling powers, but many need very short cool-down time. Up until now, there still exists a wide gap between the cooling requirements for various applications and the availability of the applicable miniaturized cryocoolers. The open-loop Joule-Thomson cryocooler (JT) has acted as the traditional backbone of the rapid cool-down cryocoolers for a long time. However, serious disadvantages such as the susceptibility to plugging of the valve, the intrinsic inefficiency and especially, the very short

cooling duration make their use impractical for numerous important applications requiring reliable, efficient cooling and a much longer cooling duration. There has been a growing interest in miniaturizing regenerative cryocoolers such as the Stirling cryocooler and the SPTC, especially for the latter. Similar to the JT, there is also no any moving component at the cold end of the SPTC, thereby greatly facilitating the miniaturization. Compared with the Stirling cryocooler, the SPTC is also well known for its long life and high reliability [13].

Normally, the cooling capacity of a regenerative cryocooler would decrease sharply with reduced size, and an effective solution to this problem is to increase both the charge pressure and the cycle frequency to compensate for the decrease in working fluid volume. However, a too high operating frequency often results in the poor heat transfer in the regenerative heat exchanger, thereby producing considerable irreversible losses. The CFD method is an effective approach of systematically analyzing the internal process in a SPTC. Based on the developed two-dimensional axis-symmetric CFD model, we have modeled the oscillating flow and heat transfer processes in the micro coaxial SPTC operating at 90–170 Hz without either double-inlet or multi-bypass while using the inertance tube with a gas reservoir as the only phase-shifter. The model indicates that there exists an optimum frequency for the given dimensions: too low a frequency leads to a strong mix between warm and cold fluids, thereby considerably deteriorating the cooling performance, whereas too high a frequency would produce the downward sloping streams flowing from the warm end to the axis and nearly puncturing the gas displacer from the warm end, thereby creating larger temperature gradients in radial directions and thus undermining the cooling performance. The above studies help to thoroughly understand the underlying mechanism of the micro SPTC operating at very high frequencies and provide a theoretical foundation for its practical design and optimization. Figure 3 shows the schematic and the 2-D axis-symmetric CFD model of the micro coaxial SPTC without either double-inlet or multi-bypass [13].

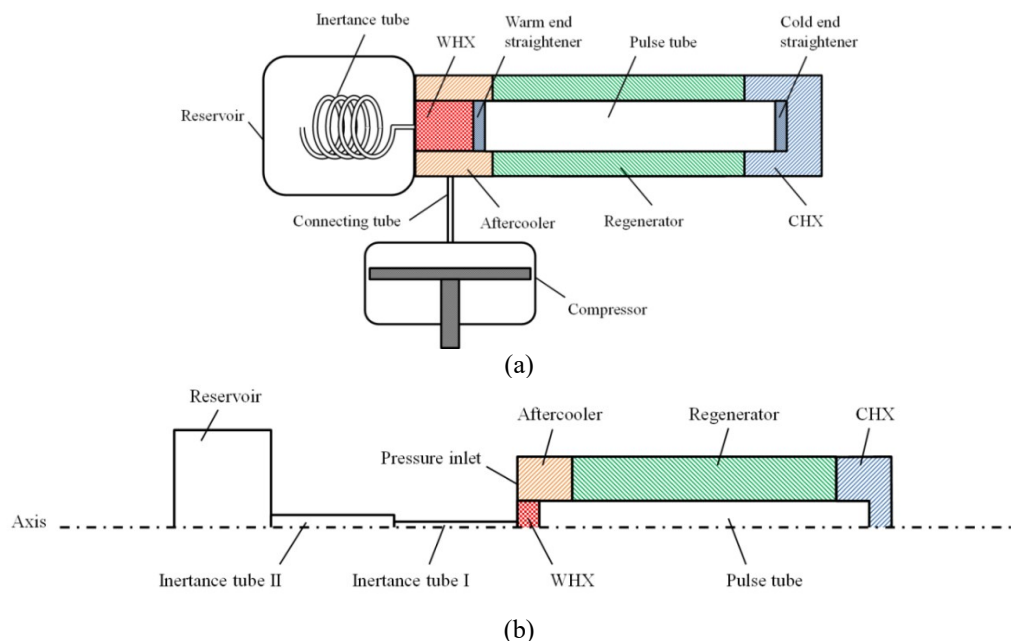


Figure 3. The micro coaxial SPTC without either double-inlet or multi-bypass.
(a) Schematic; (b) 2-D axis-symmetric CFD model.

Based on the above theoretical analyses, a 800 g micro coaxial SPTC has been worked out. It operates at 144 Hz and can provide 1.2 W at 80 K with an electric input power of 60 W. The cool-down time is 6.2 minutes. Figure 4 shows the actual micro SPTC.



Figure 4. The 800 g micro coaxial SPTC operating at 144 Hz.

3. Two-stage SPTC

The main purpose of developing the two-stage SPTCs is to simultaneously achieve the cooling capacities at both stages, in which the second stage normally works in 30–35 K while the first stage usually operates in 80–150 K. The capacity in distributing the cooling capacities between the stages has been investigated theoretically and experimentally.

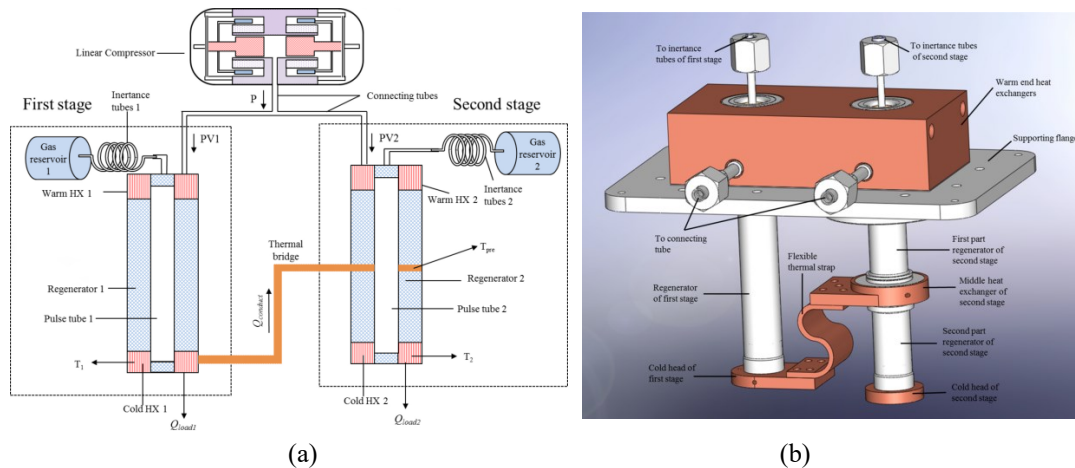


Figure 5. The thermally-coupled two-stage SPTC. (a) Schematic; (b) Construction of the cold finger.

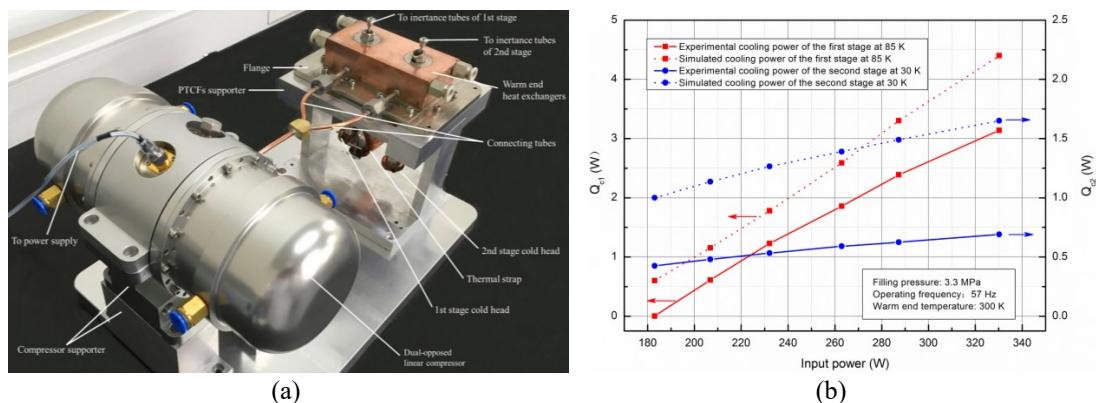


Figure 6. (a) Actual two-stage SPTC; (b) Performance characteristics.

A theoretical model of the thermally-coupled two-stage SPTC based on the electric circuit analogy with considering real gas effects has been established, and simulations of both the cooling performances and PV power distribution between stages has been conducted. The results indicate that the PV power is inversely proportional to the acoustic impedance of each stage, and the cooling capacity distribution is determined by the cold finger cooling efficiency and the PV power into each stage together. A thermally-coupled two-stage SPTC is developed and tested, and the results show that it can reach a no-load temperature of 17 K and simultaneously achieve 0.69 W at 30 K and 3.1 W at 85 K with an electric input power of 330 W and a reject temperature of 300 K [14].

4. Three-stage SPTC

The development of the three-stage SPTCs mainly targets applications at around 10 K, as well as precooling for J-T coolers to achieve liquid helium temperatures. Both thermally-coupled and gas-coupled arrangements of the three-stage SPTC have been studied, as shown in Figure 7. And the entropy analysis has been employed as one of the main approaches for their design and optimization [15].

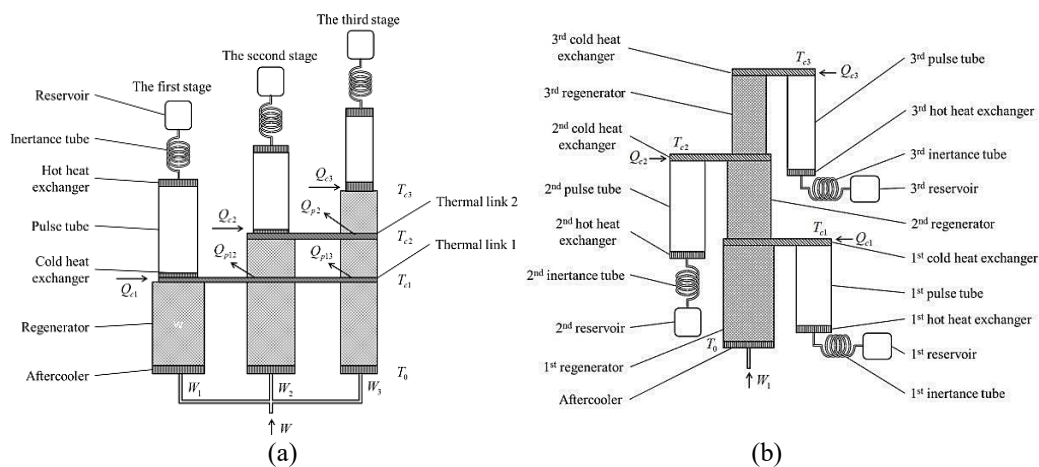


Figure 7. (a) Schematic of three-stage thermally-coupled SPTC; (b) Schematic of three-stage completely gas-coupled SPTC.

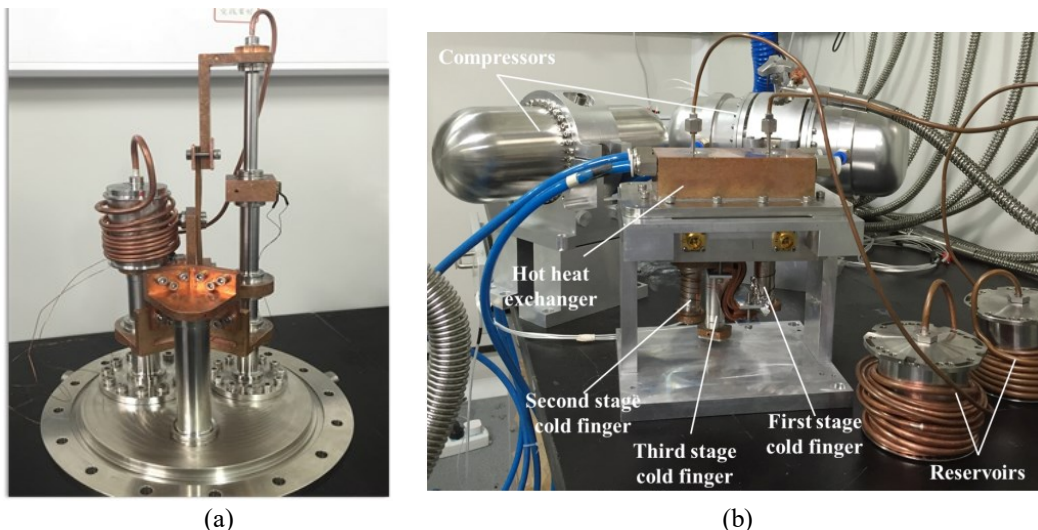


Figure 8. (a) Photo of three-stage cold finger; (b) Photo of three-stage SPTC set-up.

The thermally-coupled three-stage SPTC has been designed and implemented, as shown in Figure 8. The cooling performance of the third stage can be found in Figure 9. With a gross electric input power of 680 W, the three-stage SPTC has reached the no-load temperature of 8.9 K, and can achieve 38.2 mW at 10 K [16].

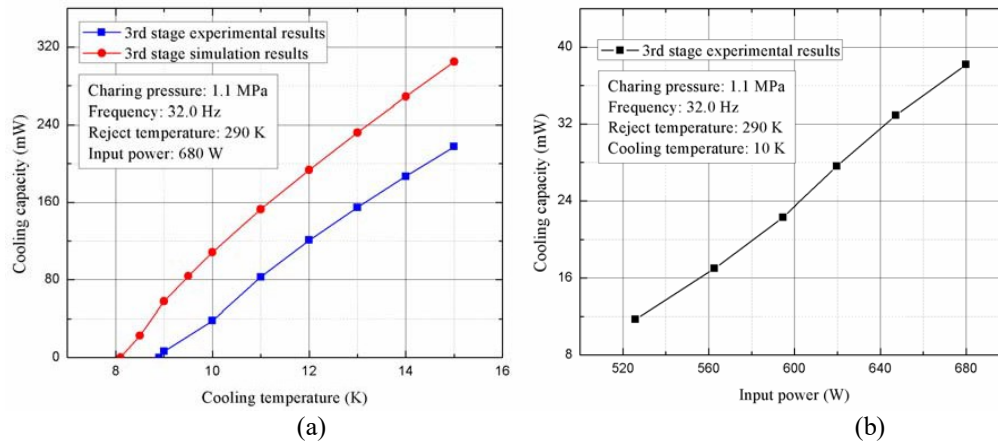


Figure 9. The cooling performance of the third-stage.

(a) Cooling capacity Vs. Cooling temperature; (b) Cooling capacity Vs. Input power.

5. Four-stage SPTC

Four-stage SPTCs are under development in order to directly achieve liquid helium temperatures using the SPTC technology only. These coolers are expected to play an important role in cooling the space low-Tc superconducting devices and in the deep space exploration as well.

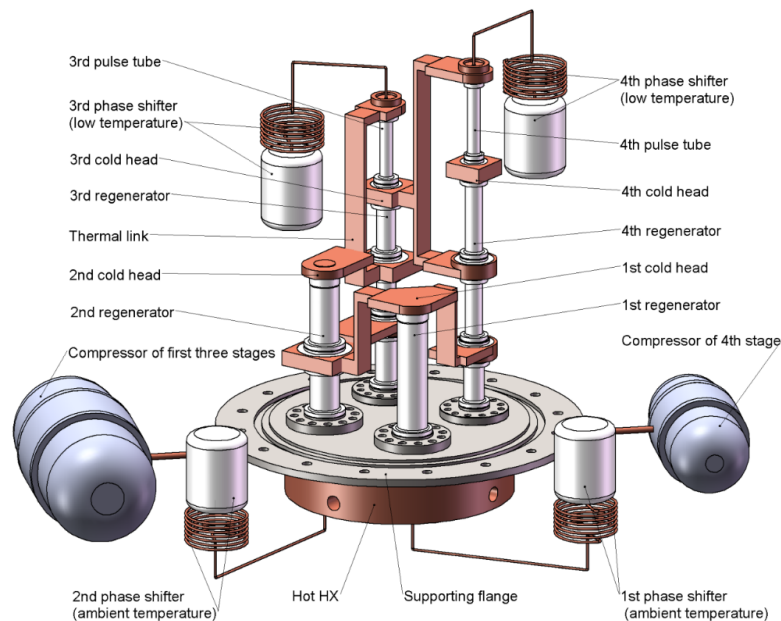


Figure 10. Schematic of the four-stage SPTC.

The schematic of the four-stage SPTC is shown in Figure 10. It is driven by two compressors, of which one drives the first stages, and the other drives the fourth stage. The preliminary simulated results show that it can achieve a cooling power of 50 mW at 4.2 K with a gross electric input power of 700 W.

6. Conclusions

This paper presents a review of recent advances in single- and multi-stage SPTCs for space applications developed at NLIP/SITP/CAS. Several typical development programs are described and an overview of the cooler performances is presented.

References

- [1] Dang HZ, Zhang L, Tan J. Dynamic and thermodynamic characteristics of the moving-coil linear compressor for the pulse tube cryocooler: Part B – Experimental verifications. *International Journal of Refrigeration*, Vol.69, pp.497–504, 2016.
- [2] Dang HZ, Zhang L, Tan J. Dynamic and thermodynamic characteristics of the moving-coil linear compressor for the pulse tube cryocooler. Part A: Theoretical analyses and modeling. *International Journal of Refrigeration*, Vol.69, pp.480–496, 2016.
- [3] Dang HZ, Tan J, Zhang L. Theoretical and experimental investigations on the optimal match between compressor and cold finger of the Stirling-type pulse tube cryocooler. *Cryogenics*, Vol.76, pp.33–46, 2016.
- [4] Dang HZ. Development of high performance moving-coil linear compressors for space Stirling-type pulse tube cryocoolers. *Cryogenics*, Vol.68, pp.1–18, 2015.
- [5] Zhang L, Dang HZ, Tan J, Song YY, Zhou BL, Zou RQ, Zhao YB, Gao ZQ, Bao DL, Li N. Theoretical and experimental investigations on the partial scaling method for the Oxford-type moving-coil linear compressor. *Cryogenics*, Vol.69, pp.26–35, 2015.
- [6] Tan J, Dang HZ. An electrical circuit analogy model for analyses and optimizations of the Stirling-type pulse tube cryocooler. *Cryogenics*, Vol.71, pp.18–29, 2015.
- [7] Dang HZ. High-capacity 60 K single-stage coaxial pulse tube cryocoolers. *Cryogenics*, Vol.52, pp.205–211, 2012.
- [8] Dang HZ. 40 K single-stage coaxial pulse tube cryocoolers. *Cryogenics*, Vol.52, pp.216–220, 2012.
- [9] Dang HZ, Wang LB, Yang KX. 10W/90K single-stage pulse tube cryocoolers. *Cryogenics*, Vol.52, pp.221–225, 2012.
- [10] Tan J, Dang HZ. Effects of the driving voltage waveform on the performance of the Stirling-type pulse tube cryocooler driven by the moving-coil linear compressor. *International Journal of Refrigeration*, Vol.75, pp.239–249, 2017.
- [11] Dang HZ, Zhao YB. CFD modeling and experimental verification of a single-stage inertance tube coaxial Stirling-type pulse tube cryocooler operating at 30–35 K using the mixed stainless steel mesh regenerator matrix. *Cryogenics*, Vol.78, pp.40–50, 2016.
- [12] Bao DL, Tan J, Zhang L, Gao ZQ, Zhao YB, Dang HZ. A two-dimensional model of regenerator with mixed matrices and experimental verifications for improving the single-stage Stirling-type pulse tube cryocooler. *Applied Thermal Engineering*, Vol.123, pp.1278–1290, 2017.
- [13] Zhao YB, Dang HZ. CFD simulation of a miniature coaxial Stirling-type pulse tube cryocooler operating at 128 Hz. *Cryogenics*, Vol.73, pp.53–59, 2016.
- [14] Tan J, Dang HZ. Theoretical and experimental investigations on the cooling capacity distributions at the stages in the thermally-coupled two-stage Stirling-type pulse tube cryocooler without external precooling. *Cryogenics*, Vol.82, pp.48–61, 2017.
- [15] Gao ZQ, Dang HZ. Entropy analyses of the three-stage thermally-coupled Stirling-type pulse tube cryocooler. *Applied Thermal Engineering*, Vol.100, pp.944–960, 2016.
- [16] Gao ZQ, Dang HZ, Bao DL, Zhao YB. Investigation on a three-stage Stirling-type pulse tube cryocooler for cooling the low-Tc SQUID. *IEEE Transactions on Applied Superconductivity*, Vol.27, No.4, June 2017, doi: 10.1109/TASC.2016.2642584.

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