Review of recent advances in Stirling-type pulse tube cryocoolers

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Abstract. This paper reviews recent advances in Stirling-type pulse tube cryocoolers (SPTCs) developed in the authors’ laboratory, in which single- and two-stage coolers cover 10–150 K while three- and four-stage ones operate at 4–10 K. The cooling capacities vary from 1.0 W for optical and electronic devices to 580 W at 77 K for superconducting cables, while the overall masses range from 700 g to 180 kg. The three-stage SPTCs are developed mainly for the applications at around 10 K, while the four-stage ones are to directly achieve the liquid helium temperature. The three-stage and four-stage SPTCs can simultaneously acquire cooling powers at three and four stages, respectively, and both of them can also be used to precool the J-T coolers for further lower temperatures. The typical development programs are introduced and an overview of the cooler performances is presented.

1. Introduction
The pulse tube cryocooler (PTC) is now recognized as a significant technological innovation in regenerative cooling technology because it eliminates any moving component at the cold end and thus achieves the high reliability at this end. The Stirling-type PTC (SPTC) driven by a linear compressor further realizes the long life of the driver at the warm end, and thus has appeal to a wide variety of applications [1]. Recently, new progresses have been made in terms of single- and multi-stage SPTCs developed in the authors’ laboratory. This paper reviews these advances and presents an overview of the cooler performances.

2. Single-stage SPTCS
A series of single-stage coaxial and in-line high efficiency SPTCs covering 20–150 K have been developed for a variety of practical applications and become mature, in which several mid-sized ones weighing 5–10 kg are already flown in space [2]. Using the mixed regenerator which consists of multi-segment matrices to enhance the regenerator performance at the colder end and also to minimize the overall flowing resistance along the tube, we have made continuous advances in the mid-sized coolers working at below 30 K, in which a no-load temperature of 20.8 K and the cooling power of 0.2 W at
25 K have been achieved with an input power of 300 W. In this paper, the significant progresses about a 700 g micro SPTC operating at very high frequencies and a 150 kg large-size high-capacity one achieving 580 W at 77 K will be focused on.

2.1. 700 g micro SPTC
Miniaturization of coolers for low-temperature applications has attracted worldwide attention because many applications based on optical and electronic technologies only require relatively small cooling powers but do need very short cool-down time. There still exists a wide gap between the cooling requirements for various applications and the availability of the applicable miniaturized cryocoolers. Normally, the cooling capacity of a regenerative cryocooler would decrease sharply with reduced size and an effective solution to it is to increase both charge pressure and cycle frequency to compensate for the decrease in working fluid volume. However, the charge pressure has an upper limit in view of safety, while a too high operating frequency often results in the poor heat transfer in the regenerative heat exchanger, thereby producing considerable irreversible losses. Based on the developed two-dimensional axis-symmetric CFD model, we had investigated the oscillating flow and heat transfer processes in the micro coaxial SPTC operating at 90–400 Hz, and a 800 g micro prototype had been worked out in 2017 [2, 3].

In 2018, the overall mass including the linear compressor has further decreased to 700 g and the Engineering Model (EM) of the cooler is achieved. The same cooling performance is kept, for which 1.2 W at 80 K can be achieved with an electric input power of 60 W and the cool-down time is about 6.2 minutes. But the EM cooler becomes more compact. Figure 1 provides a photograph showing the comparisons between the developed micro linear compressor and a conventional mid-size one, and figure 2 shows the developed 700 g micro SPTC together with a Coke can, which has been ready for practical applications.

2.2. High-capacity SPTC with the cooling capacity of 580 W at 77 K
In recent years, the continuously increasing demand for electricity has put a strain on the capacity of electric grids around the world. The high temperature superconducting (HTS) cable can provide a feasible solution to the serious problem because it can carry several times more power than the conventional one with the same footprint and operate at a much lower voltage as well. The cryogenic system is indispensible for the HTS cable, in which some requirements are essential such as low maintenance, high reliability, long operation life, high cooling efficiency, small footprint and acceptable cost. The SPTC achieves high reliability and long life at both cold and warm ends and also has other additional outstanding advantages such as structural simplicity, high cooling efficiency, compactness, and thus it is regarded as an attractive candidate for the HTS cable. One formidable challenge for the aimed application is from the required huge cooling powers. To minimize the
number of the cryocoolers needed in the cryogenic system, the cooling capacity of about 600 W up to even 1 kW at 77 K is desirable.

The linear compressor serves as the energy origin of a SPTC. There are three types of widely-used linear compressors, namely, moving-iron, moving-coil, and moving-magnet ones. The moving-coil design avoids open circuit axial forces and torques on the current carrying coil and is much easier to completely eliminate the radial forces, and thus has the higher motor efficiency, lower EMI noise, and enhanced reliability and manufacturability. The major disadvantage of it is the high cost, but in recent years we have succeeded in lowering its price to a level comparable to its moving-magnet counterpart.

The design is based on the scaling method, for which the basic principle is that if a detailed design of an ideal compressor is known, the new compressors with much larger or smaller capacities can be quickly achieved through scaling-up or scaling-down the given one while the compressor efficiency is kept nearly unchanged [1, 4]. The chosen original linear compressor is a mature one with an input capacity of 400 W developed in the same laboratory for space applications, and the aimed input capacity of this scaled-up linear compressor is about 12 kW. Based on the controlling equations of the moving-coil linear compressor, the basic scaling factor can be determined and then the dimensional parameters of the scaled-up compressor can be achieved [1, 4].

Figure 3 shows the photo of the original 400 W linear compressor (up) and the scaled-up new one with a simulated input capacity of 12 kW (down), in which the mass of the latter is about 100 kg.

![Figure 3. 400 W and 12 kW compressors](image)

![Figure 4. SPTC capable of 580 W at 77 K.](image)

In order to ease the practical application, the coaxial arrangement is adopted and all of the phase-shifters (inertance tubes) are enveloped in the reservoir to achieve a compact system. Figure 4 shows a photo of the developed high-capacity SPTC. The overall mass is 180 kg and currently it can provide the cooling power of 580 W at 77 K with the input power of 12 kW. The reject temperature at the cold end is kept at 300 K using the cycling water. A relative Carnot efficiency of about 14% is achieved, and the further optimizations in terms of both compressor and pulse tube cold finger are underway to achieve the aimed cooling capacity of over 600 W at 77 K.

3. Multi-stage SPTCs

In a series of new experiments, several high-capacity two-stage SPTCs are developed and tested, and they can reach a no-load temperature of 10.2 K and simultaneously achieve 3.0 W at 30 K and 15 W at 80 K at the reject temperature of 300 K. However, much more important progresses have been achieved in terms of three-stage and four-stage SPTCs during the last year.

3.1. Three-stage SPTCs

The three-stage SPTCs are developed to mainly target applications at around 10 K, and they can also be used for precooling J-T coolers to achieve liquid helium temperatures. Both thermally-coupled and gas-
coupled arrangements of the three-stage SPTC have been studied, and the entropy analysis has been employed as one of the main approaches for their designs and optimizations [5].

Cryogenic phase-shifting and mixed regenerator matrices are employed to improve the performance at the third stage. Simulations of the phase relationship, dynamic pressure and mass flow rate are presented with third-stage phase-shifters at 40 K, 50 K and 293 K, respectively [6]. Mixed regenerator matrices of conventional stainless steel meshes and rare-earth materials such as Er3Ni, HoCu2 and Er0.6Pr0.4 are optimized theoretically [6]. Different ratios and combinations are analyzed and compared, and the quantitative analyses by the entropy analysis are made. A three-stage SPTC without external precooling is developed based on the theoretical analyses. Figure 5 shows the concept of cryogenic phase-shifter, and figure 6 provides a photo of the actual three-stage cold fingers [6]. In the new experiments, with an overall input power of 370 W, the three-stage SPTC has experimentally reached a no-load temperature of 4.8 K and achieved a cooling capacity of 155 mW at 10 K.

The single-compressor-driven (SCD) three-stage SPTC has also been investigated [7]. The main differences between the SCD type and the multi-compressor-driven (MCD) one is that the former is driven by only one linear compressor, which will result in big differences in the distribution of the input acoustic power in each stage and the optimization of the operating parameters. The effects of the dynamic temperatures are considered to improve the accuracy of the simulation at very low temperatures, and a specific simulation example aiming at 10 K is given in which the quantitative analyses are provided [7].

In the new experiments, with a total input acoustic power of 370 W, the SCD three-stage SPTC reaches a no-load temperature of 7.2 K and achieves the cooling capacity of 67 mW at 10 K. The performance of the SCD three-stage SPTC is slightly poorer than that of its MCD counterpart given above, but the advantages of lightweight (20 kg less) and compactness make the former more attractive to practical applications.

3.2. Four-stage SPTCs
The four-stage SPTCs are developed in order to directly reach liquid helium temperatures, which can also be used for precooling a J-T cooler to achieve further lower temperatures, and thus they are expected to play an important role in cooling the space low-Tc superconducting devices and in the deep space exploration as well.

A schematic of the four-stage SPTC and the corresponding experimental set-up are shown in figures 7 and 8, respectively. The four-stage SPTC is driven by two compressors, of which one drives the first two stages, and the other drives the last two stages. The preliminary experiments show that it has achieved a no-load temperature of 4.5 K with a gross electric input power of 680 W. It can also simultaneously achieve 10 W at 80 K, 8 W at 60 K, 1.5 W at 30 K, and 10 mW at 5 K, respectively.
4. Conclusions
This paper presents a review of recent advances and new progresses in single- and multi-stage SPTCs developed in the authors' laboratory. The EM of a 700 g micro coaxial single-stage SPTC and a high-capacity one with the cooling capacity of 580 W at 77 K have been achieved. The three-stage SPTC has reached 4.8 K and the four-stage one did 4.5 K. Furthermore, they can simultaneously acquire cooling powers at three and four stages, respectively. The effective cooling capacities at well below 4 K could be expected if the J-T coolers under preparation are added to the developed three-stage or four-stage SPTCs presented above.

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