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Development of high-performance cryocoolers capable of operating from 120 K down to 5 mK

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Abstract. This paper presents a review of the recent development of a variety of high-performance cryocoolers developed in the authors' laboratory operating from 120 K down to 5 mK. Above 1.0 K, these cryocoolers involve regenerative or recuperative cycles, or employ the hybrid cycle formed by the above two ones. For the regenerative cycle, the study is focused on the Stirling-type pulse tube cryocooler (SPTC) which covers 2.2–120 K and is used to cool either infrared detectors or superconducting facilities. The hybrid cryocooler, typically composed of the recuperative J-T cooler precooled by the regenerative multi-stage SPTC. With a base temperature of 1.36 K, it is used to cool the superconducting nanowire single photon detector used in the optical quantum computers. The cryogen-free dilution refrigerator is a rising development focus in the laboratory, which aims to achieve a base temperature of 5 mK and the typical cooling powers varying from 400 μW to 1.3 mW at 100 mK for cooling the chips in the superconducting quantum computers. The application background and optimization approaches of the cryocoolers are described and summarized, and then the performance characteristics are presented and discussed.

1. Introduction

This paper presents a review of the recent development of a variety of high-performance cryocoolers developed in the authors' laboratory with the operating temperatures ranging from 120 K down to 5 mK.

Above 1.0 K, the refrigeration cycles involve regenerative or recuperative cycle, and also the special hybrid cycle composed by both of them. For the regenerative cycle, the study is focused on the SPTC because it not only has no moving component at cold end, which eliminates any wear therein and minimizes vibration and EMI, but also is driven by the linear compressor which makes it further realize long life at warm end and achieve high system efficiency. The mature miniature and mid-sized single-stage SPTCs cover 25–120 K while multi-stage ones can achieve 2.2 K with cooling capacities varying from milliwatt levels to tens of watts. These SPTCs are mainly used to provide low-noise cooling for the infrared detectors with short, medium, and long wavelengths and the cold optics systems, and several types of them are developed for space applications. A high-capacity SPTC capable of 1220 W at 77 K has found applications in the high-Tc superconducting power systems. The hybrid cryocooler, typically composed of the recuperative J-T cooler precooled by the regenerative multi-stage SPTC, is developed to achieve the lower temperatures of 1–2 K. With a no-load temperature of 1.36 K and the effective cooling powers at

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1.8 K, it is used to cool the superconducting nanowire single photon detector, which often plays an important role in the optical quantum computers.

Below 1.0 K, the cryogen-free dilution refrigerator is a rising development focus in the authors' laboratory, which aims to achieves a base temperature of 5 mK and the typical cooling powers varying from 400 μW to 1.3 mW at 100 mK so as to provide appropriate cooling for the quantum chips in the superconducting quantum computers. In this development, either the multi-stage SPTC with the cooling capacity of 2.5–4.0 W at 4.2 K, or the hybrid cryocooler with the cooling power of 1.0–2.0 W at 3.0 K, serves as the critical precooling stage for the dilution refrigerator.

The application background and optimization approaches of the various cryocoolers are described and summarized, and the performance characteristics are presented and discussed.

2. SPTCs

2.1 Single-stage SPTCs

The pulse tube cryocooler (PTC) is widely regarded as an important innovation in the regenerative cryocoolers and has achieved significant progress in the past four decades. Without any moving component at the cold end, the wear in the cold finger is eliminated, and both vibrations and EMI at the cold end are substantially reduced. Based on the driver used, the PTCs can be further divided into the GM-type PTC and SPTC. The SPTC is driven by the linear compressor which further achieves high reliabilty, long operation lifetime and light weight at the warm end, and thus has a strong appeal to a lot of important fields [1].

A series of single-stage SPTCs covering 25–120 K have been developed in which the miniature and mid-size ones are used for cooling infrared detectors or superconducting electronic devices while the high-capacity ones for cooling superconducting magnets or cables. The typical cooling capacity of the mid-size ones weighting 5–10 Kg are 20 W@100 K, 10 W@80 K, 4.0 W@60 K, 2W@40K and 1.5 W@30K, respectively.

A special micro one is developed, weighting only 700 g with a typical cooling capacity of 1.0W@77K, as shown in Figure 1(a), which can be used either in space or for cooling miniature infrared or superconducting devices which have strict requirements on the volume and weight of the cooling system.

Another special single-stage SPTC is a high-capacity one, weighting about 80 kg, which has the typical performance of 1,080–1,220 W@77 K and have already been actually used in cooling the high-Tc superconducting magnets and cables in China [2,3], as shown in Figure 1(b). A variant of it is to lower its cooling temperature down to 20 K and then achieve the typical cooling capacity of 50–100 W, which is finding its practical application in cooling the high-Tc superconducting magnets used in the developing commercial controlled nuclear fusion system.

2.2 Multi-stage SPTCs

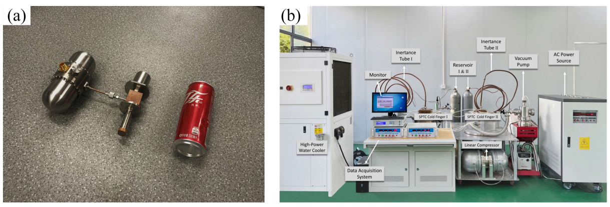

Figure 1. The developed micro and high-capacity SPTCs.

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The main purpose of developing the multi-stage SPTCs is to acquire the lower temperatures, or simultaneously achieve the cooling capacities at different temperatures.

A two-stage one weighting about 12 kg is developed which can provide the cooling powers of 12 W@95 K and 1 W@20 K simultaneously and thus is used to cooling the optics and infrared detector with the long wavelength at the same time.

The development of the three-stage SPTC mainly targets applications at around 10 K. The entropy analysis [4], cryogenic phase-shifting and mixed regenerator matrices [5] have been employed as the main approaches for their design and optimization. It weights about 15 kg and the typical cooling capacity is 0.5 W@10 K.

The four-stage SPTC is developed mainly for precooling the final stage, J-T cooler, in the hybrid cryocooler to directly achieve the liquid helium temperature and below. A typical four-stage SPTC weighting about 18 kg is developed which achieves a no-load temperature of 3.3 K [6], which makes it possible that the developed J-T cooler can be precooled by the four-stage SPTC at about 8.0 K, which is much lower than that used in the similar designs, and thus both the lower temperature and the better comprehensive performance of the developed hybrid cryocooler have been achieved.

A special multi-stage SPTC developed in the authors' laboratory is the five-stage one, as shown in Figure 2. It has achieved a base temperature of 2.2 K [7], which is the lowest temperature actually achieved by the SPTC cycle alone ever reported till now. Another important meaning of this development is that the five-stage SPTC can achieved the high cooling performance at liquid Helium temperatures, such as 2.5 W@4.2 K, which is comparable to that of a typical high-performance GM-type PTC.

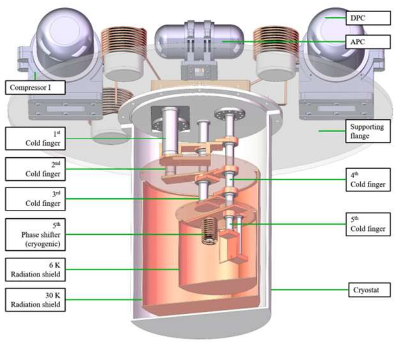

Figure 2. The developed five-stage SPTC.

2.3 Linear compressors

The linear compressor is the energy source of SPTCs. In the authors' laboratory, a series of high performance linear compressors are developed based on the flexure springs, non-contacting clearance seal, moving-coil design with dual-opposed configuration and by anylyzing the dynamic and thermodynamic characteristics [8] to achieve light weight, long life and reduced vibrations, as shown in Figure 3(a). Now it has the input power capacity of 0.5W–25kW and has becoms an enabling drivers for all of the micro, mid-size, high-capacity, and multi-stage SPTCs. Figures

3(b)and (c) provide the information about different types, capacities and batch production of the developed linear compressors.

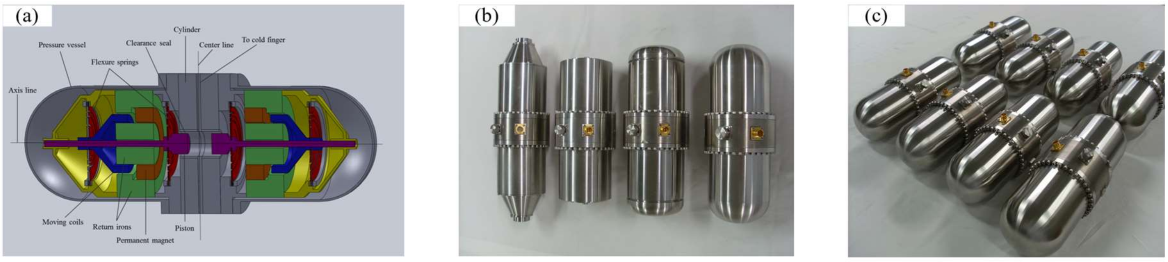

Figure 3. The developed high performance linear compressors.

3. Hybrid cryocoolers

The hybrid cryocooler is named mainly because it employs regenerative and recuperative cycles. The purpose of the development is to acquire the effective cooling at 1–2 K, which has the important applications in the infrared astronomy and the optical quantum computing as well.

In our design, the abovementioned four-stage SPTC, which adopts the regenerative cycle, acts as the precooler, and a J-T cooler, which employs the recuperative cycle, become the final stage [9, 10, 11]. A schematic of set-up of the hybrid cryocooler is shown in Figure 4(a). And Figure 4(b) gives the details of the final cold stage together with the compressors experimental apparatus.

A base temperature of 1.36 K has been reported, and it has been used in actually cooling the superconducting nanowire single photon detector (SNSPD) similar to that used in the optical quantum computer developed in China.

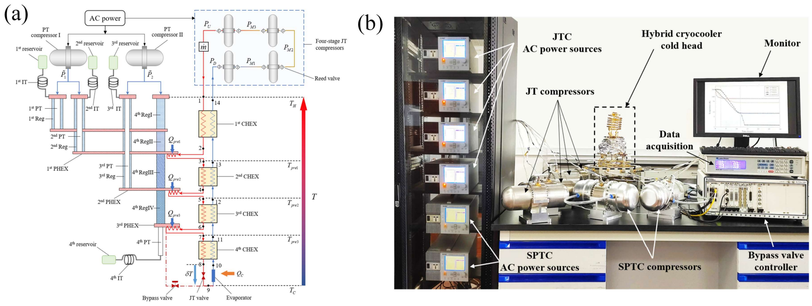

Figure 4. The developed hybrid cryocooler.

4. Dilution refrigerators

The cryogen-free dilution refrigerator is a rising development focus in the authors' laboratory [12, 13, 14]. The dilution refrigerator achieves the millikelvin temperatures by utilizing the properties of a mixture of ^{3}He and ^{4}He. Compared with other approaches, the dilution refrigerator has several significant advantages such as continuous and stable operation, low vibrations and EMI, and high cooling capacity, and thus has found a lot of practical applications, especially for cooling the chips in the superconducting quantum computers.

A schematic of the cryogen-free dilution refrigerator developed in the authors' laboratory is shown in Figure 5. The abovementioned five-stage SPTC with the typical cooling capacity of 2.5W@4.2K is used as the precooling unit. The similar J-T cooler used in the abovementioned hybrid cryocooler together with the ^{3}He and ^{4}He mixing chamber becomes the dilution unit. The pumping unit is used to cycle the whole system.

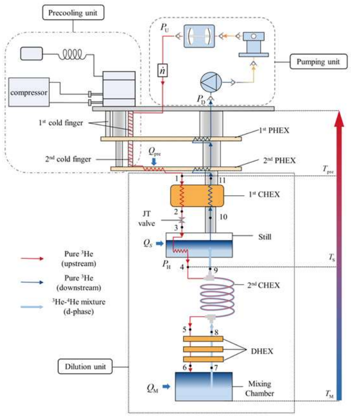

Figure 5. Schematic of the cryogen-free dilution refrigerator.

A schametic of the details of the key components of the developed cryogen-free dilution refrigerator is shown in Figure 6(a). And Figure 6(b) provides a photo of the actual system. The

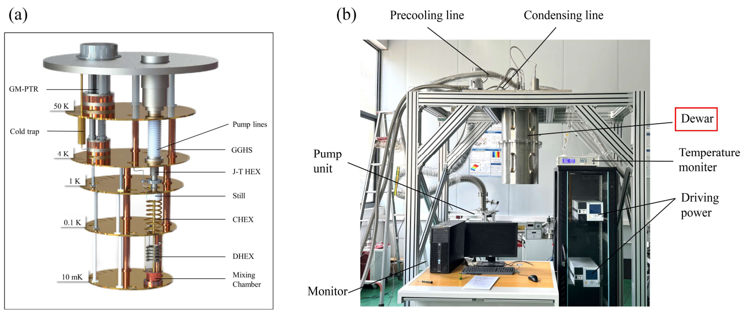

Figure 6. Details of key components and photo of the developed cryogen-free dilution refrigerator

design goal of the dilution refrigerator is to achieve the typical cooling power of 30 μW@20 mK and 1.3 mW@100 mK, respectively, with a base temperature of 5.3 mK. At present, the cooling powers of 10 μW@20 mK and 460 μW @100 mK, have been acquired, respectively, and a no-load temperature of 11.6 mK is achieved. The further optimization is under way.

5. Conclusions

In this paper, recent development in the authors' laboratory of a variety of high-performance cryocoolers from 120 K down to 5 mK is reviewed. Single- and multi-stage SPTCs cover 4.2–120 K for infrared and superconducting applications, while a no-load temperature 2.2 K and the meaningful cooling capacity of 2.5 W@4.2 K are achieved. A high-capacity SPTC capable of 1220 W at 77 K has found applications in the high-Tc superconducting power systems. The hybrid cryocoolers have achieved a no-load temperature of 1.36 K and have been used to cool the similar SNSPD used in China's optical computer. The dilution refrigerators are making good progress based on the success of both SPTCs and hybrid cryocoolers, with the aimed 30 μW@20 mK and 1.3 mW @100 mK and a base temperature of 5.5 mK, which would become the promising candidates for use in the developing superconducting quantum computers with more qubits.

Acknowledgements

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