Application of Stirling pulse tube cryocoolers in high temperature superconducting filters subsystems

Y B Duan\textsuperscript{1,2}, J Wang\textsuperscript{4}, S S Wu\textsuperscript{1,2}, W Wang\textsuperscript{3}, R J Huang\textsuperscript{1,2}, L F Li\textsuperscript{1,2*}, Y Zhou\textsuperscript{1*}

\textsuperscript{1}Chinese Academy of Sciences Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Beijing 100190, China
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing 100049, China
\textsuperscript{3}Songshan Lake Materials Laboratory, Dongguan, Guangdong 523808, China
\textsuperscript{4}CASIC Space Engineering Development Co.Ltd, Beijing 100854, China

E-mail: zhouyuan@mail.ipc.ac.cn; laifengli@mail.ipc.ac.cn

Abstract. The application of high temperature superconducting (HTS) filter has penetrated into various fields. In recent decades, GM-type pulse tube cryocooler and Stirling-type pulse tube cryocooler (SPTC) are two common cryocoolers. Due to the advantages of PTCs, such as no moving parts at the cold end, simple structure, small mechanical vibration and longer lifetime, pulse tube cryocoolers is gradually replacing oil-lubricated Stirling coolers and G-M cryocoolers to cool down HTS magnets. In this paper, the development of PTC in HTS magnet cooling in the past 20 years is summarized firstly. Secondly, the development of HTS cooling system in our lab are reported. At last, the further development direction of HTS’s cooling system is discussed.

1. Introduction

With the continuous development of HTS applications, cryocoolers are becoming more and more widely used in HTS fields (such as HTS motors) \cite{1}. HTS series products will demand higher standard on cryocoolers, such as high efficiency, high compactness, high reliability and low vibration. In the liquid nitrogen temperature region, cooling power from several watts to hundreds of watts is required \cite{2}. The SPTC is more superior than traditional displacer-type Stirling cryocooler in low vibration and stability and have participated in many practical applications. A detailed review of these cryocooler used in HTS field in the past 20 years is given as following.

2. Stirling-type pulse tube cryocooler

2.1 Large-cooling power Stirling-type pulse tube cryocooler

In the past 20 years, PTCs employed in the field of HTS have become more and more mature. B.Gromoll et al. have done some research on the application of 25 K PTCs in HTS devices \cite{3}. As shown in Figure 1, the influence of different filling patterns on the performance of PTC in the heat regenerator are compared. A pulse tube cryocooler of 75 W@ 50 K and 55 W@ 50 K is designed for HTS equipment, and the input electric power is 8.5 KW and 5.3 KW, the corresponding COP are 0.9% and 1.0% respectively; In 2004, a PTC with a cooling power of 200 W at 77 K and an input power of 4 KW was developed by the Advanced Cryogenic Refrigeration group at Praxair for HTS series applications. At 77 K operation, its Carnot efficiency is 13%, and the compressor efficiency is 84%\cite{4}; After further
improvement and optimization, they developed a PTC with a cooling power of 300 W at 80K in 2007, and the Carnot efficiency is as high as 19% [5]. SA Potratz et al. developed a Stirling-type with a cooling power of 1 KW and a Carnot efficiency of 13% in 2008 [6]. The PTC, as shown in Figure 2, served for the HTS market. As is known to all, the effect of the non-uniformity of the temperature of the regenerator on the pulse tube has been studied. The large-cooling power SPTC, as shown in Fig.3, used a mixture of copper and brass wire mesh to reduce the loss caused by temperature non-uniformity. When the input power is 8.9 KW, it obtained 298 W cooling power at 71 K [2]. In 2011, Daming Sun et al. reported a SPTC for cooling HTS motors, which can provide 150 W of cooling at 80 K with 3.83 KW of input power[7]. As shown in Figure 4, Hu et al. developed a 500 W @ 80 K coaxial high-efficiency PTC for HTS system, and the Carnot efficiency reached 18.2% [8].

![Figure 1. B.Gromoll et al. designed 75W@50K PTC](image1)

2.2. Small cooling power Stirling-type pulse tube cryocooler
In addition to the large-cooling power PTCs mentioned above, some small HTS components such as superconducting filters require some low-cooling power cryocoolers. In 2002, the Institute of Physics and Chemistry of the Chinese Academy of Sciences(TIPC) developed a low-frequency coaxial PTC with liquid nitrogen temperatures for HTS filters. After optimizing the regenerator filling and the cold-end heat exchanger, the cooling power is 6 W @ 75 K, the lowest temperature is 25.6 K [9]. In 2005, Jung-Won Nam et al. used a Stirling cryocooler to precool the PTC in order to cool the HTS motor, the experimental device is shown in Figure 5. Although the performance of the PTC is not satisfactory, reaching 55 K, it has confirmed the feasibility of using the PTC to cool the superconducting motor[10]. In 2005, Dang et al. reported a non-magnetic coaxial PTC for high-temperature SQUID, which can obtain a cooling power of 130 mW at 80 K with an input power of 72 W[11]. Liang et al. from Technical

![Figure 2. Designed solid model and manufactured 1KW cold cryocooler](image2)
Figure 3. Schematic diagram of Zhejiang University high power PTC [2]

Figure 4. 500 W@ 80K PTC developed by Hu et al [8].

Institute of Physics and Chemistry, Chinese Academy of Sciences (TIPC) used a compressor with a capacity of 10 cm$^3$ to design a 2 W @ 58 K cryocooler with a range of 40-80 K for cooling HTS devices [12]. In 2011, Taekyung et al. reported a SPTC using a slit heat exchanger for cooling a superconducting motor or generator. The slot heat exchangers have different structures and have no contact thermal resistance problems. The 400 mesh stainless steel wire mesh filled by the device. The experimental results show that it has sufficient thermal efficiency. When the temperature is 59.5 K and 65.5 K, the cooling power is 7 W and 10 W, and the Carnot efficiency is 10.9% and 14.1%, respectively [13]. Zhang et al. designed and manufactured a linear PTCs with a cooling power of up to 10 W at 90 K for HTS and spaceborne infrared photo detector. It has partially optimized the PTCs, the influence of different parameters (operating frequency, cooling power) on the input power of PTC is compared. We know from the graph, when the cooling power of PTC is 8 W @ 90 K, the working frequency is 48 Hz [14]. The cooling power and input power have a linear relationship. In the regenerative low temperature cryocooler, the regenerator is an extremely critical component, which has a significant impact on the performance of the cryocooler. Then Shanghai University of Science and Technology also researched a high temperature pulse tube cryocooler, but the experimental results showed that compared with the operating frequency, the charging pressure has more influence on the pulse tube cryocooler [15].
Therefore, for more detailed operating frequency and charging pressure, the internal mechanism is not particularly clear. In 2018, Liu et al. tested a space application cryocooler. The study found that under 2.5 MPa and 51 Hz, the compressor efficiency was 88% and the Carnot efficiency reached 16.08% [16].

![Figure 5](image)

**Figure 5.** Jung-Won Nam et al. designed Stirling-type PTC [10]

3. Cryocooler with the cooling power of 3W at 77 K

Our lab uses a pulse tube cryocooler that provides 3 W cooling power at 80 K to cool down a HTS filter. As shown in Figure 6, the parameters of this cryocooler are shown in Table. 1.

The PTC needs a good heat dissipation structure to work, or the cooling efficiency of this cryocooler is low. In the experimental results, we will introduce the work done on the heat dissipation structure.

The experimental system mainly includes a cryocooler, a vacuum chamber, a temperature acquisition system, and a superconducting filter system. The vacuum cavity is designed as a rectangular vacuum cover with a maximum vacuum of 5E-5 Pa; The temperature acquisition system uses a PT100 platinum resistance thermometer.

![Figure 6](image)

**Figure 6.** (a) 3 W@77 K PTC Physical Picture; (b) Physical photos of HTS integrated system.

4. Experiment and discussion

4.1. Room temperature heat load analysis and optimization

To reduce the loss of cryocooler performance due to poor heat dissipation, we simulated and calculated the heat dissipation of the compressor. According to the calculation results, we designed the fins for the heat dissipation of the compressor. When installing the fins, we used the aerospace thermal adhesive to
reduce the thermal resistance, and chose the appropriate fan. Thermometer and a heater to simulate the heat load; The system uses a combination of fins and fans, the fan power is 12 W; The superconducting filter is shown in Figure 7.

Table 1. Main parameter of the cryocooler

| Category                        | Parameter                      |
|---------------------------------|--------------------------------|
| Operating temperature           | -20 °C + 50 °C                 |
| Rated input power               | 80 W                           |
| Rated cooling capacity          | 3 W @ 77 K                     |
| Cooling capacity                | 5 W @ 77 K                     |
| No-load temperature             | ≤ 47 K                         |
| Weight                          | 2.4 kg                         |
| Temperature control accuracy    | ± 0.1 K                        |
| Installation direction          | Any direction                  |

![Figure 7](image)

(a) Physical picture of compressor with fins; (b) Physical picture of HTS filter.

According to the heat conduction model of straight ribs with constant cross section, the relationship between the height L and height h of the fin and the heat dissipation Φ can be expressed by the following formula:

$$\Phi = -\lambda A_L \frac{d\theta}{dx} \bigg|_{x=0} = \sqrt{hU \lambda A_L \theta dh(m)}$$  \hspace{1cm} (1)

$$m = \sqrt{\frac{hU}{\lambda A_L}}$$ \hspace{1cm} (2)

We selected four materials: red copper, aluminum, brass and 304 stainless steel for comparison. Figure 8 shows the simulation results of the height, width, thickness, convective heat transfer coefficient and heat dissipation of four different materials:

From the above results (Figure 8), it can be seen that the heat dissipation effect of stainless steel 304 is the worst. The heat dissipation effect of red copper, aluminum and brass is not much different in the small size range, but the difference becomes larger as the size increases, considering the economic cost and other issues, aluminum is finally used as the material of the fin for processing. The calculated fin size is that the rib thickness is 2 mm, the rib height is 32 mm, and the rib length is 20 mm. The compressor uses 30 miniaturized aluminum fins for every 20 W heat discharged to the environment.
When the ambient temperature is 298 K, the convective heat transfer coefficient can be selected as 50 W/(m²K). When the system is running at the rated power, the fin temperature is maintained at 308 K, which meets the design requirements.

![Figure 8](image)

**Figure 8.** The relationship between fin size and convective heat transfer coefficient and heat dissipation under different materials

Figure 9(a) is an experimental result of the structure shown in Figure 7. After the heat dissipation optimization of the compressor, the temperature of the compressor tends to be stable gradually during the operation of 30 min. The temperature of the compressor before and after optimization is 322 K and 314 K respectively. After optimization, the working temperature of the compressor decreases by 8 K, and the temperature of the compressor decreases obviously after the refrigerator reaches the steady state. The temperature of the hot end begins to stabilize within five minutes, and the temperature gradually stabilizes at 309 K and no longer rises. However, the temperature rising rate of the hot end is higher than that of the compressor within five minutes. The reason is that the hot end temperature measurement thermometer is installed on the heat exchanger made of copper, while the compressor temperature measurement point is installed on the outer stainless steel shell. Because the thermal conductivity of copper is much larger than that of stainless steel, the temperature at the hot end temperature measurement point is higher than the temperature at the compressor temperature measurement point in a short time.

### 4.2 PTC performance test and analysis

Figure 9(b) shows that when the rated input power of the cryocooler is 80 W and the working frequency is 75 Hz, the cooling capacity of the cryocooler increases linearly with the rise of the cold head
temperature. When the temperature of the cold head is 80 K, the cooling capacity is basically the same, which is little affected by the ambient temperature. When the hot-end temperature is 300 K, the typical cooling capacity is 3 W @ 77 K.

![Figure 9](image1.png)

**Figure 9.** (a) Comparison of temperature rise curves of compressor and pulse tube hot end; (b) Relationship between cold head temperature and cooling capacity

![Figure 10](image2.png)

**Figure 10.** (a) The relationship between cold head temperature and input work under different heating loads; (b) Cold head cooling curve under different heating loads

As shown in Figure 10(a), under different cold end loads, the input power decreases with the increase of the cold head temperature. At the cold head temperature of 80 K and an ambient temperature of 295 K, when the load rises from 0 W to 3 W, the input power is increased from 27 W to 90 W, the typical cooling capacity is 3 W @ 77 K, the input power is 90 W, and the relative Carnot efficiency is 10.4%. In this filter subsystem, there are radiation heat leakage, filter signal line heat conduction heat leakage, and air heat conduction. After analysis, compared with the heat conduction and heat leakage of the signal line, the radiation heat leakage and air convection heat transfer can be ignored, and the heat conduction and heat leakage of the signal line is about 0.8 W. On the other hand, the power consumption of the filter is 1.6 W. The rated cooling capacity of this chiller at 77 K is 3 W, and the sum of the thermal power consumption of these two parts must be less than 3 W to satisfy the normal operation of the filter subsystem at 77 K. At the same time, from the Figure 10(b), we can see the relationship between the cooling time and the cold head temperature of the cooler under the working frequency of 75 Hz, the charging pressure of 4.5 MPa under the condition of 90 W input power. No matter the load is 0 W or 3 W, the cooler can drop to the lowest temperature in ten minutes.
5. Conclusion
This paper summarizes the application and development of pulse tube cryocooler used for HTS in recent 20 years. And developed a set of pulse tube cryocooler for HTS filter to provide a low temperature platform and cooling capacity, the typical cooling capacity is 3 W@ 77 K. Through the optimized design of the heat dissipation of the hot end of the compressor and the pulse tube, the temperature of the hot end is maintained at 310 K, and the cooling with no load can be reduced to 47 K within 10 minutes. The change curve of cooling capacity input power with cold head temperature and the change of cooling capacity with different discharge temperature of hot end were tested. Pulse tube cryocooler in the future in the field of high temperature superconductor can play a greater role will be an indispensable link in the field of high temperature superconductor.

6. References
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