# Design of a 30K Single-Stage Free-Piston Stirling Cryocooler

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## ABSTRACT

Free-piston Stirling cryocooler (FPSC) is promising in cooling down electronic and high temperature superconducting (HTS) devices. Currently, most of the FPSCs work around 77 K due to their high thermal efficiency and compact size. Most recently, a two-stage FPSC aimed at providing tens of watts of cooling power at 30 K has been designed and tested by our group and the preliminary results showed positive prospect. In order to maintain the advantage of simplicity, in this work a single-stage FPSC working at 30 K is proposed on the basis of a single-stage FPSC which could efficiently supply a cooling power of 350 W at 80 K. In order to obtain a lower cooling temperature, a variable diameter regenerator is adopted in the new cryocooler. Besides, different combinations of phase shifters are compared and finally only a displacer is chosen for the new cryocooler. The simulation results show that the cryocooler can reach a no-load temperature of 24.61 K and a cooling power of about 51 W at 30K obtained simultaneously with an input acoustic power of about 3.27 kW, corresponding to a relative Carnot efficiency of 14.21%. In addition, the internal acoustic field characteristics and the performance dependences on the operating conditions are studied in detail.

## INTRODUCTION

In recent years, for the purpose of cooling high temperature superconducting (HTS) devices (such as transformers, generators or motors, etc.), the need for cryocoolers with tens of watts of cooling capacity in the range of 20–30 K has been rapidly increasing[1,2,3]. Currently, the Gifford-McMahon (GM) cryocoolers or the GM type pulse tube cryocoolers are relatively mature to meet the cooling requirements in this temperature region and are commercially available[4]. However, the existence of oil lubricated compressors with oil filters and high and low pressure tanks in GM system makes the cryocooler bulky and regular maintenance is required. In addition, the efficiency of the cryocooler is reduced by the irreversible loss due to the rotary valve. In recent decades, advances in Stirling-type pulse tube cryocooler research have brought about another alternative way to provide limited cooling power in the 30 K region[5]. The Stirling-type pulse tube cryocoolers possesses the longest lifetime span due to its elimination of moving parts at the cold end. However, the efficiency achieved was usually low resulting from the dissipation of the expansion power.

Compared with GM cryocoolers and Stirling-type pulse tube cryocoolers, Stirling cryocoolers can achieve higher efficiency and more compact structure by recovering expansion work at the cold

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end. Stirling cryocoolers can be generally classified into two categories, i.e., traditional kinematic and free piston type from the perspective of transmission. In the traditional kinematic Stirling cryocooler, displacer and power piston are rigidly connected via a mechanical linkage. The inevitable existence of oil-lubrication and a dynamic seal in kinematic Stirling cryocooler requires frequent maintenance. In contrast, in the FPSC, the displacer and the power piston are free and acoustically coupled. This configuration possesses the advantages of high reliability, high efficiency, zero maintenance and compact size. In order to provide a cooling power in the range of 20–30 K, a two-stage architecture is generally needed in FPSCs. Currently, two-stage FPSC with small cooling capacity (≤ 2W) operating in the range of 20–30 K has been well studied and used in space missions[7,8]. In order to meet the requirement of the HTS applications, most recently, a two-stage FPSC aiming at providing tens of watt cooling power at 30 K has been designed and tested by our group[9]. The preliminary results showed that a lowest cold-head temperature of 27.6 K and a cooling power of 78W at 40 K with an input electric power of 3.2 kW, corresponding to a relative Carnot efficiency of 14.8% can be achieved. However, a two-stage configuration will make the construction more complex. In order to maintain the advantage of simplicity, in this work, a single-stage configuration which can achieve similar results is proposed on the basis of a single-stage FPSC which could efficiently supply a cooling power of 350 W at 80 K[10].

This paper introduces the design of a single-stage FPSC, which aims at providing tens of watts of cooling power at 30 K. The design approach and system configuration of the new cryocooler is described first. Next, different combinations of phase shifters are compared and the optimal phase shifter is chosen in the new cryocooler. Then, the internal acoustic field characteristics of the new designed cryocooler is presented and the operating parameters' sensitivity effect on the cooling performance are studied. Finally, conclusions are drawn.

## DESIGN APPROACH AND SYSTEM CONFIGURATION

The design goal for the FPSC is to provide a cooling power of 50 W at a temperature of 30 K with a relative Carnot efficiency (with the acoustic power as input power) higher than 10%. Commercially available software Sage™ is used for numerical calculations. The mean operating pressure of the system is designed to be 3 MPa with helium as the working gas, 50 Hz is chosen to be the working frequency as the resonant frequency of the linear compressor is around 50 Hz. The phase shifter, the porosity, length and equivalent housing diameter of the cold end segment regenerator are chosen as the objects and carefully optimized.

Figure 1 illustrates a schematic of the new designed single-stage FPSC prototype, which is designed based on a developed FPSC with large cooling capacity at the liquid nitrogen temperature

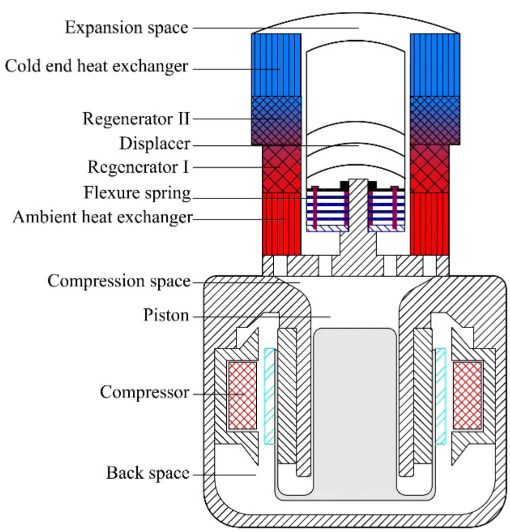


**Figure 1.** Schematic of the new designed single-stage FPSC prototype.

**Table 1.** Optimized dimensions of each components of the cryocooler

| Component | Detailed dimensions |
|---|---|
| Expansion space | 45cc |
| CHX | Equivalent diameter 107 mm<br>Length 30mm,<br>Radial-fin type, 0.2 mm in gap and 27 mm in radial height |
| Regenerator II | Equivalent diameter 107 mm<br>Length 30mm long<br>Filled with #400 stainless steel screen，0.59 in porosity |
| Regenerator Ⅰ | Equivalent diameter 104 mm<br>Length 30mm long<br>Filled with #300 stainless steel screen，0.76 in porosity |
| Displacer | Displacer diameter facing the expansion space 75mm<br>rod diameter 25 mm,<br>moving mass 1.03 kg,<br>spring constant 88.2 kN/m |
| AHX | Equivalent diameter 104 mm,<br>Length 35 mm<br>Radial-fin type, 0.5 mm in gap and 20 mm in height |
| Compression space | 300cc |

in our group. The FPSC consists mainly of a cooler and a linear compressor. The cooler includes a regenerator, a displacer, an ambient heat exchanger (AHX) and a cold end heat exchanger (CHX), a compression space and an expansion space. The optimized dimensions of each components of the cryocooler are listed in Table 1. In order to achieve a lower cooling temperature, a variable diameter regenerator is adopted. The regenerator includes two segments (Regenerator I and Regenerator II), and the porosity and equivalent housing diameter of the two segments are different. The hot end segment of the regenerator (Regenerator I) is filled with 300-mesh stainless-steel screens with a porosity of 0.76 and the cold end one (Regenerator II) with a larger equivalent diameter is filled with 400-mesh stainless-steel screens with a porosity of 0.59. The AHX and CHX are of the radial-fin type. Heat load is rejected by the circulating cooling water at the AHX. Both the heat exchangers and the regenerator are located in the annular space outside the displacer. Flexure bearings are used to support and center the displacer. The features of this type of arrangement include compact size and easy assembly.

A moving-magnet type linear compressor which was manufactured by Zhongke Lihan (Shenzhen) Thermoacoustic Technologies Co. Ltd is used to provide acoustic power to the cooler. The compressor adopts a single piston configuration to realize a compact structure. The nominal input electrical power of the compressor is 5 kW, the maximum current is 50 A, and the maximum displacement of the piston is 14.2 mm. The compressor is expected to deliver more than 3 kW of acoustic power to the cooler and the compressor efficiency is expected to be above 80%.

## SIMULATION RESULTS AND DISCUSSIONS

### Comparison of different phase shifters

In order to obtain an ideal phase difference between the pressure wave and volume flow rate in the regenerator, a phase shifter is indispensable in a FPSC. According to the design experience in single-stage Stirling-type pulse tube cryocooler working at the range of 20–30 K[11,12], the phase shifter in a FPSC should be carefully chosen to obtain a lower cooling temperature with single-stage structure. Therefore, different combinations of phase shifters are compared herein to determine which combination should be employed in the new cryocooler.

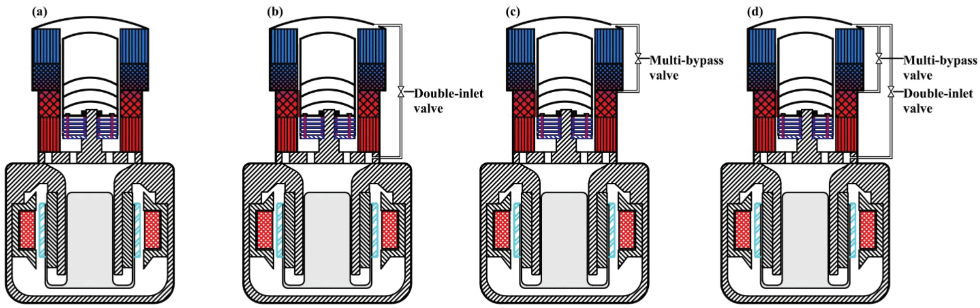


**Figure 2.** Schematic of different combinations of phase shifters: (a). Only Displacer; (b). Displacer + double-inlet; (c). Displacer + multi-bypass; (d). Displacer + double-inlet+ multi-bypass.

**Table 2.** Comparison of different combinations of phase shifters

| Types of phase shifters | Maximum cooling power at 30K /W | Relative Carnot efficiency /% | No-load temperature /K | Pressure ratio in the compression space | Pressure ratio in the expansion space | Phase angle in the compression space /° | Phase angle in expansion space /° |
|---|---|---|---|---|---|---|---|
| Only Displacer | 58.33 | 16.05 | 24.65 | 1.44 | 1.40 | -68.96 | 69.50 |
| Displacer + Double-inlet | 46.72 | 12.84 | 25.73 | 1.45 | 1.41 | -69.01 | 69.53 |
| Displacer + Multi-bypass | 44.90 | 12.34 | 25.91 | 1.45 | 1.41 | -69.14 | 69.60 |
| Displacer + Double-inlet + Multi-bypass | 31.77 | 8.72 | 27.09 | 1.45 | 1.41 | -69.11 | 69.57 |

Figure 2 shows the schematic of different combinations of phase shifters and Table 2 shows the calculation result. From Table 2, we can see that when the displacer only act as the phase shifter (as shown in Figure 2 (a)), the cryocooler can provide a maximum cooling power of 58.33 W at the temperature of 30 K with an input acoustic power of 3.27 kW, corresponding to a relative Carnot efficiency of 16.05%. When the displacer and the double-inlet are adopted as the phase shifters (Figure 2 (b)), the maximum cooling power decreases to 46.72 W with an identical input acoustic power, and when displacer combines with the multi-bypass (Figure 2 (c)), the maximum cooling power further declines to 44.90 W. When the multi-bypass and the double-inlet accompanied with a displacer, are employed as the phase shifters (Figure 2 (d)), only a maximum cooling power of 31.77 W can be obtained at the temperature of 30 K. This implies that unlike the Stirling-type pulse tube cryocoolers, the adoption of multi-bypass and double-inlet as phase shifters in the new cryocooler has no positive, but some negative effects on the cooling performance. One possible explanation is that, on one hand, the introduce of multi-bypass and double-inlet in the new cryocooler decreases the mass flow rate through the cold end of the regenerator, thus the cooling capacity of the working gas in the cold end declines accordingly; on the other hand, the phase shifting effect of the displacer can provide the required acoustic impedance for the cooler sufficiently, and the

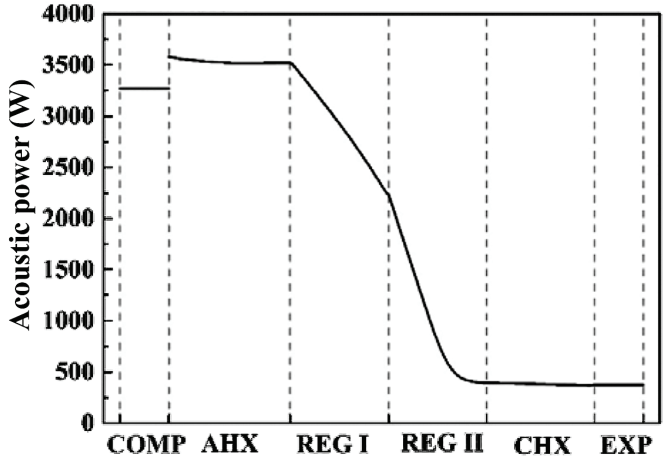


**Figure 3.** Distribution of acoustic power inside the cooler (REG denotes regenerator, COMP and EXP denote compression space and expansion space, respectively).

introduction of the multi-bypass and the double-inlet has limited effect on the phase shifting effect of the cryocooler. Therefore, only a displacer is employed as the phase shifter in the new designed single-stage FPSC.

### Internal acoustic field characteristics

In order to understand the internal acoustic field characteristics of the new designed cryocooler, the axial distributions of some key acoustic field parameters, for instance, acoustic power, gas mean temperature and phase difference between dynamic pressure wave and volume flow rate are presented in Figure 3–5. The origin of the coordinate is set at the piston surface adjacent to the compression space, then the positive direction points to the compression space, AHX, Regenerator I, Regenerator II, CHX, and finally the expansion space.

Figure 3 illustrates the numerical results for the distribution of acoustic power inside the cooler. An acoustic power of approximately 3.27 kW flows into the cooler through the compression space and reaches the AHX after confluence with acoustic power recovered by displacer. Across the AHX, acoustic power is consumed in the two segments of the regenerator to transfer entropy from CHX to

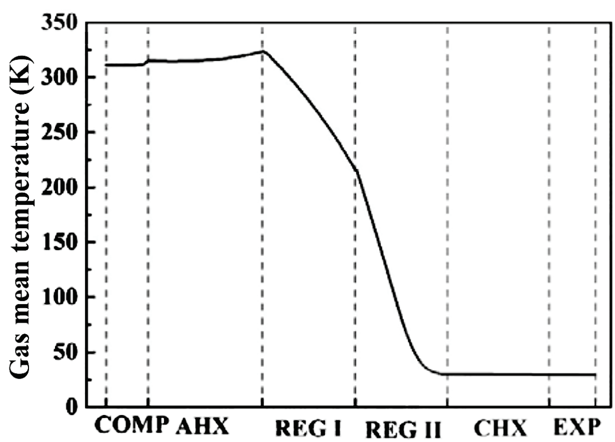


**Figure 4.** Distribution of gas mean temperature inside the cooler.

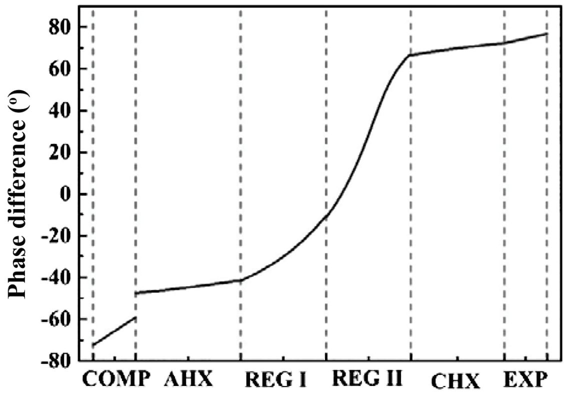


**Figure 5.** Distribution of phase difference between dynamic pressure wave and volume flow rate inside the cooler.

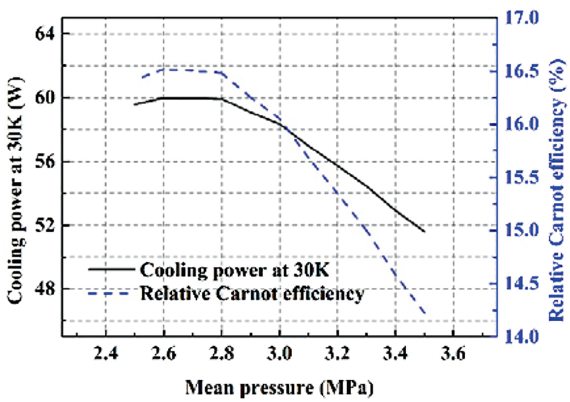


**Figure 6.** Influence of the mean pressure on the cooling performance.

AHX, thereby obtaining a cooling effect. The first and second segment of the regenerator consume approximately 1285 W and 1800 W acoustic power, respectively. The remaining acoustic power flows into expansion space through CHX, and approximately 310 W acoustic power is recovered to compression space by the displacer.

Figure 4 shows the distribution of gas mean temperature inside the cooler, the gas temperature in the cold end of Regenerator I approaches 215 K. In Regenerator II, the temperature gradient is relatively larger than Regenerator I.

Figure 5 shows the distribution of the phase difference between dynamic pressure wave and volume flow rate inside the cooler. As shown, the phase difference between the dynamic pressure wave and the volume flow rate varies from -41.8° to -11.2° in the first segment of regenerator, and -11.2° to 66.6° in the second segment of regenerator, indicating that an in-phase relationship between the dynamic pressure wave and volume flow rate has been obtained inside the hot end of Regenerator II, i.e., the middle of the regenerator.

**Influence of the working conditions**

The mean pressure and operating frequency play important roles on the cooling performance of the cryocooler. In this section, we investigate these two parameters to see how they affect cooling performance.

The influence of the mean pressure is shown in Figure 6. When the input acoustic power is kept constant at 3.27 kW, both the cooling power and thermal efficiency go up firstly and then drop

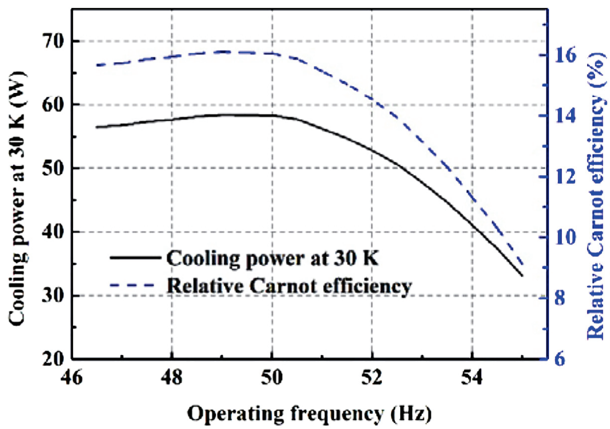


**Figure 7.** Influence of the operating frequency on the cooling performance.

slowly after reaching their maximums at 2.7 MPa of mean pressure. When the mean pressure increases from 2.7MPa to 3.5MPa, the cooling power drops by about 13.9 % and the relative Carnot efficiency drops by about 13.8%, which indicates that the cooling performance of the cryocooler is sensitive to the mean pressure.

Figure 7 presents the influence of the operating frequency. As shown, when the operating frequency increases from 45 Hz to 55 Hz, the cooling power first increases from 56.51W to 58.38 W and then decreases to 33.14 W sharply. Similarly, the related Carnot efficiency first rises from 15.66% to 16.07% and then decreases to 9.13% sharply. The optimal cooling performance is obtained at the operating frequency of 49 Hz. When the operating frequency is higher than 50 Hz, the severe performance degradation in both cooling power and efficiency could be attributed to the considerable deterioration of heat transfer between stainless-steel mesh and working gas caused by the decrease of thermal penetration depth of working gas.

## CONCLUSIONS

This paper presents the design of a single-stage FPSC, which aims at providing tens of watt cooling power at 30 K. In order to obtain lower cooling temperature, a variable diameter regenerator is adopted in the new cryocooler. Besides, different combinations of phase shifters are compared and finally only displacer is employed in the new cryocooler. The simulation results show the cryocooler can reach a no-load temperature of 24.65 K and a cooling power of about 58.33 W at 30K can be obtained simultaneously with an input acoustic power of about 3.27 kW, corresponding to a relative Carnot efficiency of 16.05 %. The structural modification is currently underway and some experimental results will be acquired in near future.

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