Numerical investigation on non-equal section regenerators performance for pulse tube cryocooler

QL Zhu\textsuperscript{1,2}, YJ Liu\textsuperscript{1}, J Quan\textsuperscript{1}, ZL Wang\textsuperscript{1}, HL Chen\textsuperscript{1\*} and JT Liang\textsuperscript{1,2}

\textsuperscript{1}Key Laboratory of Space Energy Conversion Technologies, Technical Institute of Physics and Chemistry, CAS, Beijing 100190, China
\textsuperscript{2}University of Chinese Academy of Sciences, Beijing 100190, China

E-mail:hlchen@mail.ipc.ac.cn

Abstract. It is always been a research hotspot to improve the overall efficiency of Stirling pulse tube cryocoolers (SPTCs). The regenerator as the vital component directly determines the performance of SPTCs. Therefore, an approach to improve the overall efficiency is provided by improving the performance of the regenerator. The factors for the influence of the three regenerators structure on the overall efficiency are analyzed and discussed by an 8W@80K SPTC Sage model. The simulation results show the optimal overall efficiency of SPTC with three different regenerators structure varies with the compressor PV power input. Moreover, in terms of the overall efficiency, the smaller the regenerator volume is, the higher overall efficiency will be obtained. Specifically, the overall efficiency of a SPTC with the non-equal (variable and conical) section regenerators is increased by 14.7% and 50% respectively compared with the equal (constant) section regenerator, which theoretically proves the feasibility of this method.

1. Introduction

SPTCs have the characteristics of low vibration, wear resistance, high reliability and long service life owing to no moving parts at the cold-end. It is gradually replacing the Stirling cryocooler and becoming an important space and even ground cryocooler type application. However, with the cold-end displacer removed, the cold-end phase angle between the pressure wave and mass flow is difficult to adjust to the optimum, resulting in an overall efficiency that is lower than the Stirling cryocooler. Therefore, how to improve the overall efficiency of SPTCs becomes a research hotspot.

Since the 1980s, the development of SPTCs technology has become increasingly mature. Especially in the liquid nitrogen temperature zone (60K~120K), the relative Carnot efficiency of SPTCs have had been improved from less than 10% to over 20%. In 2015, Wang X T et al. from the Institute of Physics and Chemistry of the Chinese Academy of Sciences (TIPC) adopted an active phase shifter to replace the inertertance tube+gas reservoir with an opposite ambient displacer with which the relative Carnot efficiency of the cryocooler can reach 24.2% at 80K[1]. However, for the passive phase shifter SPTCs, the overall efficiency is lower than the active phase shifter since it does not recover the PV power at the hot-end. A single-stage SPTC driven by a 20cc swept volume compressor was developed by National Institute of Standards and Technology (NIST), and a cooling capacity of 18.8W@90K was reached at an operating frequency of 45Hz and an input PV power of 222W, the relative Carnot efficiency was 20% approximately[2]. In 2018, after a series of optimizations and improvements, a large-cooling capacity SPTC in the 60K temperature zone was successfully developed by the Key
Laboratory of Space Energy Conversion Technologies. A cooling capacity of 11.2W and a relative Carnot efficiency of 19.55% at 80K was obtained with the 160W electric input power, but its relative Carnot efficiency was only 15.9% at 60K simultaneously[3]. The relative Carnot efficiency of SPTCs in the liquid nitrogen temperature zone remains about 20% after a series of optimizations including the match relationship between the compressor and cold finger, the size of the cold finger, the filling methods of the regenerative material and the structure of phase shifter by many researchers[4-12]. It can be seen that the conventional optimization methods have been difficult to improve the overall efficiency of SPTCs, but higher efficiency of SPTCs is beneficial to its own development and applications.

Based on the above, this paper proposes a method to improve the overall efficiency of SPTCs by applying the variable and conical section structure to the regenerator. The factors for the performance improvement of these two structures are analyzed and some laws are obtained based on an 8W@80K SPTC Sage model, which have certain guiding significance for the design and optimization of the regenerator in the future.

2. System configuration
In order to facilitate the extraction of simulation parameters and subsequent experimental research, a single-stage SPTC driven by a linear dual-opposed compressor is selected as the research object. The regenerator and pulse tube in the cryocooler are arranged in a U-shape to ensure the operability of the regenerator simulation and 400 mesh stainless steel screens are filled in the regenerator. The inercance tube and gas reservoir are also chosen to achieve phase adjustment at the hot-end. According to the selection of components and structures, an 8W@80K single-stage SPTC Sage model in the liquid nitrogen temperature zone is established. The U-shape SPTC structure diagram is shown in Figure 1.

![Figure 1. The schematic of single-stage U-shape SPTC](image)

3. Regenerator structure
The regenerator is the vital component of SPTCs, and its efficiency determines the overall efficiency. At present, the heat exchange efficiency between the working gas and regenerative material is mainly improved by changing the regenerative material and the filling methods of the regenerative material, which can directly improve the overall efficiency. However, as is known the gas density rises sharply as the temperature decreases, and its volume flow decreases under the same mass flow. At the same time, the useless volume of the regenerator could be greatly reduced if the regenerator volume decreases. The ineffective volume flow can be decreased to reduce the PV power loss of the compressor and improve the overall efficiency simultaneously. Based on this, three types of regenerator models were established. We divided the regenerator into two parts: the regenerator near the ambient temperature is called regenerator I, and the regenerator near the cold-end is called regenerator II. The two parts of the regenerator directly connects and the diameters of the three types of regenerator I are the same, but the structure of regenerator II is different. In order to reach the maximum COP, the variable section location
is not necessarily at the middle of regenerator, but the three regenerators have the same total length, as shown in figure 2. The specific structural dimensions are shown in Table 1.

**Table 1. Simulation parameters of three regenerators**

| Parameters                  | Values         |
|-----------------------------|----------------|
| Diameter I (mm)             | 30             |
| Diameter II (mm)            | 30             |
| Length (mm)                 | 64             |
| Regenerator volume (cc)     | 45.21          |
| Cold-end (K)                | 80             |
| Hot-end (K)                 | 300            |
| Variable section            | 30             |
| Variable section            | 25.4           |
| Variable section            | 38.71          |
| Variable section            | 80             |
| Variable section            | 300            |
| Conical section             | 30             |
| Conical section             | 27~18          |
| Conical section             | 300            |
| Conical section             | 23.36          |
| Conical section             | 80             |
| Conical section             | 300            |

4. Simulation results and discussion

All models were built by Sage software. In this paper, three single pulse tube cryocoolers with different regenerator structures were established. The user can find the corresponding numerical solution by giving the corresponding mass flow and temperature boundary conditions. In addition, the Sage model provides with optimization functions, for example, when the cold-end temperature is set to be constant, the maximum cooling capacity at this temperature can be calculated by optimization.

The cryocooler operating frequency, the cold-end phase angle and other parameters influenced by changing the regenerator structure will affect the overall COP. Therefore, a compressor with the same parameters, an average pressure of 3.5MPa and an ambient end of 300K were selected to ensure the comparability of the simulation results. However, the operating frequency and phase shifter were optimized for each type of regenerator to achieve the best COP under this structure. In addition, the maximum COP at 80K and the maximum cooling capacity at 80K with the input PV power of 150W were selected as the optimization target.

Normally, we use the relative Carnot efficiency to measure the performance of the pulse tube cryocooler. The overall relative Carnot efficiency calculated by sound power η can be expressed as:

\[ \eta = \frac{Q_{net}}{W_{pv}} \times \frac{T_a-T_c}{T_c} \]  

where \( Q_{net} \) is the net cooling power that the cold-end can obtain at 80K, \( W_{pv} \) is the PV power provided by the compressor, \( T_a \) and \( T_c \) are the ambient temperature and the cold-end temperature respectively.

4.1 Typical cooling performance

Figure 3 shows the cooling performance curves of the three cryocoolers with different regenerator. It can be seen from the figure that the cryocooler with the conical section regenerator obtains the
maximum cooling capacity and the cryocooler with the constant section regenerator obtains the minimum cooling capacity at the same cooling temperature and input PV power. In the temperature range of 40K~80K, the cooling capacity slope of the constant section and the variable section structure is basically similar, and with the increase of the refrigeration temperature, the cooling capacity slope of conical section structure increases continuously. The cryocooler with the conical section regenerator can obtain the cooling capacity of 12.43W at 80K, and a relative Carnot efficiency of 22.78% can be achieved, however, the cryocooler with the constant section regenerator can only obtain the cooling capacity of 8.275W at 80K, and the relative Carnot efficiency is only 15.17%, which is 33.4% lower than the cryocooler with conical section regenerator.

From the figure 4, we can conclude that the cryocoolers COP increase first and then decrease as the input PV power increases and they all display the maximum COP. The input PV power of the three cryocoolers are not similar when the COP reaches its maximum, the optimal COP of the cryocooler with constant, variable and conical section regenerator can be obtained when the input PV power is 140.3W, 119.9W and 100.3W, respectively. As the regenerator volume decreases, the input PV power at the optimum COP decreases, but the optimum COP improves obviously.

**Figure 3.** The cooling capacity of three cryocoolers with different regenerator structure

**Figure 4.** The curves of COP as input PV power changes

4.2 Effects of the regenerator structure on pressure ratio, volume flow and phase angle
The PV power is transferred into the system and is a measure of the gas energy. Each node position has PV power if the cryocooler can be divided into many parts. Based on the researches before, the PV power is given by[13-15]:

\[
\text{PV power} = \text{PV power if cryocooler can be divided into many parts}
\]
\[ W_{pv} = \frac{1}{2} P_m V_m \cos \theta \]  

where \( P_m \) and \( V_m \) are the pressure amplitude and volume flow amplitude of the gas flow, and \( \theta \) is the phase angle between pressure wave and volume flow (volume flow leads pressure wave to positive).

Figure 5 shows the change in pressure ratio at different locations in PTC. From the connecting tube to the pulse tube, the pressure ratio decreases monotonically and the pressure ratio of the cryocooler with the conical section regenerator is highest no matter which position. Compared with the others, the cryocooler with the constant section regenerator owns the lowest pressure simultaneously. The behavior suggests that the pressure ratio increase is possibly caused by the decrease in the volume of the regenerator and the increase in internal resistance of the regenerator which is caused by the decrease of the cross section. From the diagram we can see that the smaller the regenerator volume is, the higher the \( P_m \) is, and the largest the \( W_{pv} \) is. Meanwhile, the pressure ratio slopes of the regenerator with conical and variable sections are steeper than the constant section regenerator which indicates that the flow resistance of the conical and variable section regenerator are bigger than the constant section regenerator. It is because of these two reasons that the pressure rises which can result in a larger cooling capacity. Figure 6 shows the change in volume flow at different locations in the PTC. The three curves change in a roughly similar trend. But there are some differences in volume flow at the cold-end, the volume flow decreases with the decrease of regenerator volume, but the cooling capacity is improved which indicates that a smaller swept volume associated with a variable and conical section regenerator can achieve the same cooling capacity compared with that of a constant section regenerator.

Figure 5 The curves of pressure ratio as the position in PTC changes

Figure 6 The curves of volume flow as the position in PTC changes
In addition, the phase angles between the pressure wave and volume flow are shown in figure 7. The phase angle at the cold-end is the most critical to the cooling performance of cryocooler. The cryocooler can obtain an optimal cooling capacity when the phase angle is 0 degree at the middle of the regenerator and -30 degree at cold-end. The phase angle of three cryocoolers are -12.89°, -5.59° and 4.87° at cold-end respectively. In terms of numerical values, the cold-end phase angle of the variable and conical section regenerators are farther away from the optimal phase angle leading to a negative impact on cooling capacity compared with the constant section regenerator. Some suitable phase shifters need to be added to achieve a better cooling performance.

![Figure 7](image)

**Figure 7** The curves of phase angle as the position in PTC changes

### 4.3 Effects of the regenerator structure on regenerator losses

In addition to the impact of key internal parameters for the cryocooler, the regenerator losses are shown to reveal the reason for the increase in the overall efficiency simultaneously, as shown in figure 8. The term AEfric shows the available energy loss for friction, while the terms AEQw and AEQx represent the available energy loss for heat exchange loss and axial heat transfer loss. For the AEfric, the three regenerator structures have similar losses because of their considerable resistance. The AEQx monotonically decreases from the constant section to the conical section owing to the reduction of heat transfer area which can effectively reduce axial heat loss based on the Fourier's law. In addition, the reduction of AEQw is the same as AEQx, which may increase the heat transfer coefficient because the decrease of cross section, resulting in an increase in gas flow velocity. In the view of the total losses, those of the variable and conical section regenerator are less than the constant section regenerator, thereby the overall efficiency improved by the same operating condition.

![Figure 8](image)

**Figure 8** Simulated available energy losses of three structure regenerators
5. Conclusions
Three geometrically different types of regenerators are established and some vital internal parameters are analyzed simultaneously, providing a series of conclusions with reference values. Firstly, the pressure ratio improves with the decrease of regenerator volume and the increase of regenerator resistance which is the most critical factor for the overall efficiency improvement. Although the volume flow and phase angle have varying effects on the overall efficiency, the overall efficiency is still improved owing to the increase of the pressure ratio. Secondly, the main losses of the regenerators are examined and show that the variable and conical section regenerator can improve the overall efficiency compared with the constant section regenerator by improving heat transfer efficiency to reduce the heat transfer loss. Finally, the constant, variable and conical section regenerator can obtain 8.274W, 9.49W and 12.43W, respectively when the cold-end temperature is 80K and the input PV power is 150W. Finally, the overall efficiency of the variable and conical section regenerator are increased by 14.7% and 50%, respectively.

6. References
[1] Wang X T, Zhang Y B, Li H B, et al. A High Efficiency Hybrid Stirling Pulse Tube Cryocooler[J]. AIP Advances 5, 037127, 2015
[2] E. D. Marquardt and R. Radebaugh. Pulse tube oxygen liquefier. Advances in Cryogenic Engineering, Vol. 45, Plenum Press, New York, 2000
[3] Wang N L, Zhao M G, Ou Y Y, et al. A high efficiency coaxial pulse tube cryocooler operating at 60K[J]. Cryogenics, 2018, 93: 48-50
[4] Nguyen T V, Raab J, Durand D, et al. Small high cooling power space cooler. Advances in Cryogenic Engineering, AIP Publishing, 2014, 1573(1): 365-370
[5] Raab J, Tward E. Northrop Grumman aerospace systems cryocooler overview[J]. Cryogenics, 2010, 50(9): 572-581
[6] Chan C K, Nguyen T, Jaco C, et al. Highcapacity two-stage pulse tube cooler[J]. Cryocooler 12, 2002:219-224
[7] Olson J, Champagne P, Roth E, et al. Very high capacity aerospace cryocooler. Advances in Cryogenic Engineering, AIP Publishing, 2012, 1434(1): 161-167
[8] Liu X T. Investigation on 9W@80K Class High Capacity Coaxial Pulse Tube Cryocoolers[D]. Beijing: Chinese Academy of Technical Institute of Physics and Chemistry, 2014 (in Chinese)
[9] Hu J Y, Dai W, Luo E C, et al. Development of high efficiency Stirling-type pulse tube cryocooler[J]. Cryogenics, 2010, 50(9): 603-607
[10] Dang H Z, Wang L B, Wu Y N, et al. Development of SITP’s Large Capacity High Frequency Coaxial Pulse Tube Cryocoolers[J]. Georgia Institute of Technology, 2011
[11] Dang H Z. High-capacity 60K single-stage coaxial pulse tube cryocoolers[J]. Cryogenics, 2012, 52(4-6): 205-211
[12] Zhang A K, Chen X, Wu Y N, et al. Study on a 10W/90K in-line pulse tube cryocooler[J]. Cryogenics, 2012, 52(12): 800-804
[13] Yang L W, Xun Y Q, Thummes G, et al. Single-stage high frequency coaxial pulse tube cryocooler with base temperature below 30 K. Cryogenics, 2010, 50: 342-346
[14] Radebaugh R. Thermodynamics of Regenerative Refrigerators. Published. In: Generation of low temperature and its applications 2003, Japan, p. 1-20.
[15] Zhang A K, Wu Y N, Liu S S, et al. High-efficiency 3 W/40 K single-stage pulse tube cryocooler for space application[J]. Cryogenics, 2018, 90: 41-46

Acknowledgments
This work is supported by the National Key R&D Program of China (Grant No.2018YFB0504600, No.2018YFB0504603) and the National Natural Science Foundation of China (Grant No.51806228).