High Efficiency 5 W at 60 K Pulse Tube Cryocooler for Infrared Sensors

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ABSTRACT

A high-capacity single-stage coaxial pulse tube cryocooler operating at around 60K has been developed for infrared sensors. The design considerations are presented, and the optimizations on the length of regenerator are described with the Sage cryocooler model. In an experiment, the influences of the regenerator length on the optimal frequency are obtained. The results show that decreasing the regenerator length can increase the optimal frequency of cryocooler. The experimental model of the cryocooler provides a cooling power of 5W at 60K with an input power of 160W, which achieves a Carnot efficiency of 12.5% . An engineering model of the cryocooler has been developed, which provides the cooling power of about 7 W at 60K with 250 W electrical power rejecting at 300K, and achieves a Carnot efficiency of about 11.2%.

INTRODUCTION

The HgCdTe infrared detectors designed for LWIR (Long Wave Infrared) applications operate best at around 60K. Pulse tube cryocoolers (PTCs) have the advantages of long life, low vibration, and high reliability. Many efforts have been made to improve the efficiencies of PTCs in the past ten years, and recently reported PTCs data have comparable efficiency to Stirling cryocoolers [1-2]. Thus, the PTCs have already become the new generation of space cryocoolers.

The past decade has witnessed a boom in the development of PTCs in China, and many high efficiency PTCs have been built. In 2011, Hu [3] developed a 5W at 60K coaxial PTC with an electric power of 150W. In 2012, Dang [4] built a coaxial PTC, which provided 4W at 60K and obtained a 9.4% of the Carnot efficiency. In 2015, Zhang [5] designed a 6W at 60K coaxial PTC with a relative efficiency of 12%. In our group, we developed a coaxial 5.7W at 60K PTC in 2014. And in 2018, a high efficiency coaxial PTC was also built, which had a cooling power of 6W at 60K with 150W input power [6-7].

Our group has conducted the research on PTCs for over twenty years. A number of coaxial PTCs have been manufactured, and all of them have worked well for years. In this paper, based on the demands of a high efficiency PTC used in HgCdTe infrared detectors, we designed a coaxial PTC working at 60K using a Sage model. The design goals and the design details are presented. The experiments were also carried out to measure the operation performance of the PTC. At the end, the performance of some engineering models are presented.

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Table 1. The design goals of the PTC

Parameters	Design
Stage arrangement	Single stage
Geometrical arrangement	Coaxial
Phase shifter	Inertance tubes and reservoir
Frequency	50±10Hz
Hot end temperature	300K
Cold end temperature	60K
Cooling power	≥5W
Electrical power	≤250W
Mass of the PTC	≤10kg

DESIGN OF PTC

Design Goals

Table 1 gives key development goals of the PTC for long wave HgCdTe infrared detectors. The cryocooler is required to provide 5W at 60K with an input electrical power less than 250W. The frequency is restricted to 40Hz – 60Hz. The weight is not expected to be higher than 10kg. The geometrical arrangement is chosen to be the coaxial configuration, because the coaxial PTCs are more convenient to be coupled with the heat load than other configurations. Besides, the coaxial PTCs have more compact structure, which is more attractive for the space infrared applications. As for the phase shifter, only the inertance tubes and reservoir are used as the phase shifter.

Design of Regenerator Length

A PTC is composed of a compressor, a cold figure and a phase shifter. The cold-finger is the main component for cooling, so the design of PTC will concentrates on the cold-finger. Considering the restriction on the frequency, in this part, the optimization of the frequency will be discussed in details.

According to the conservation of mass in the regenerator, the relationship between mass flow rate at hot end and mass flow rate at cold end can be calculated by Equation (1)

$$\dot{m}_h = \dot{m}_c + \frac{i2\pi f P A_{rg} L_{rg}}{R T_r} \tag{1}$$

where $\dot{m}_h$ is the hot-end mass flow rate, $\dot{m}_c$ is the cold-end mass flow rate, i is the imaginary unit, f is frequency, P is the dynamic pressure, A_{rg} is the cross sectional area of regenerator, L_{rg} is the length of regenerator, R is the gas constant per unit mass, and T_{rg} is the mean temperature of regenerator.

For a given cold-finger, the A_{rg} , L_{rg} and T_{rg} are constant, and P changes little when the input power to a given compressor is constant. Then, according to Equation (1), it can be concluded that the $\dot{m}_h$ will increase with the frequency at a fixed $\dot{m}_c$. In that case, the magnitude of the regenerator losses becomes high as the hot-end mass flow rate is increased. This will decrease the efficiency of PTC. To keep the mass flow rate within a reasonable range, the $A_{rg}L_{rg}$ must be reduced when the f increases.

For a coaxial cold-finger, it is easier to change the regenerator length than the cross-sectional area. Thus, the optimal frequencies at different regenerator lengths were simulated by a SAGE model and the results are illustrated in Figure 1.

Figure 1 shows the simulation results of COP (cooling power/PV power) changing with the frequency at four regenerator lengths. It should be noted that, for each regenerator length, there is an optimal frequency for maximum COP. The optimal frequency is increased with decreasing regenerator length. Also shown in Figure 1, the optimal frequency is higher than 40Hz when the regenerator length is shorter than 60mm. However, the COP decreases as the regenerator length shortens. Therefore, when both the COP and the optimal frequency are considered, 60mm is chosen to be an optimal regenerator length.

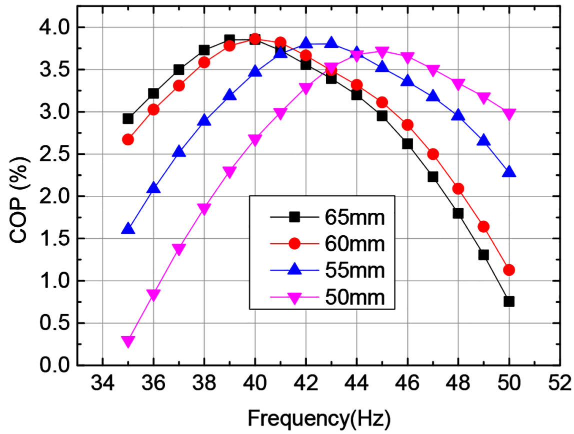

Figure 1. Simulation results of COP varying with the frequency at different regenerator length

EXPERIMENTAL OPTIMIZATIONS

Next, an experimental apparatus was built, and some experiments were carried out. The compressor was designed by our group. It is a dual opposed-piston flexure-bearing moving coil compressor, with a maximum swept volume of 10cc. The cold-finger is designed to be a separated configuration, different coaxial regenerators and pulse tubes could be connected to the same hot-end, which is convenient to conduct experiment with different regenerator lengths. The phase shifter is a three-segmented inertance tubes and a gas reservoir.

Optimization of Cold-Finger Length

To validate the results of the theoretical analysis, three regenerator lengths were manufactured. Figure 2 shows the cooling powers and optimal frequencies of the three regenerator lengths; 55mm, 60mm and 65mm. As shown in Figures 1 and 2, the experimental results confirm the analytical predictions. The PTC with longest regenerator length has the highest cooling power and lowest optimal frequency Considering both frequency and cooling power, , 60mm was chosen as the suitable regenerator length. However, the PTC with 60mm regenerator length has a cooling power of 5.2W at 60K. Considering the loss of converting the PTC from an experimental model to an engineering model, the cooling power of this PTC is insufficient. Therefore,another optimization was performed.

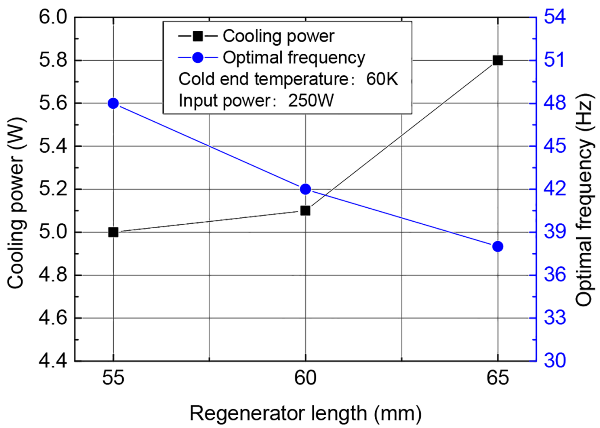

Figure 2. Experimental results of cooling power and optimal frequency at different regenerator length

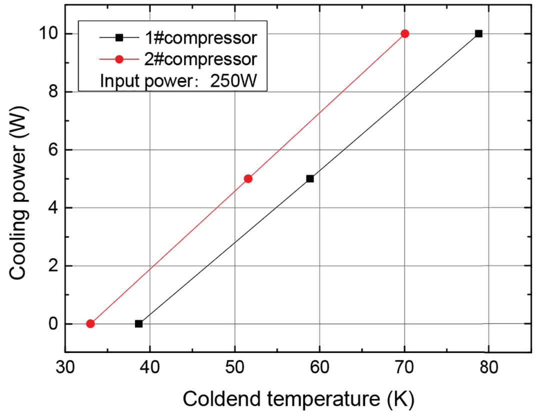

Figure 3. The performance of PTC with two kinds of compressors

Optimization of Compressor

During testing, it was found that the efficiency of the compressor (PV power/ electric power) was lower than 65%. This indicated the compressor was not a suitable match for the cold finger. Therefore, based on the coupling mechanism between compressor and cold-finger, a new compressor was designed and manufactured. As shown in Figure 3, 1# compressor is the original compressor and 2# compressor is the re-designed compressor. When the PTC was coupled with the new compressor, the cooling power of the PTC was increased from 5.2W to 7.2W at 60K with an input electrical power of 250W. Currently, this experimental PTC is capable of providing a cooling power of 5W at 60K with only 160W electric power, and a relative Carnot efficiency of 12.5%.

ENGINEERING MODELS

After the successes of the design and results of an experimental PTC, five preliminary engineering models were built. Figure 4 shows the photo of an engineering model. The 5 units were tested to measure the cooling performance.. As labeled in Figure 5, the average cooling power of the five engineering models is approximately 7W at 60K with an electric power of 250W. This indicates that the design and fabrication are relatively mature. The cooling powers of the engineering models are a little lower than the experimental model. The reason being that the connection-tube length of the engineering model is a little longer than that of the experimental model.

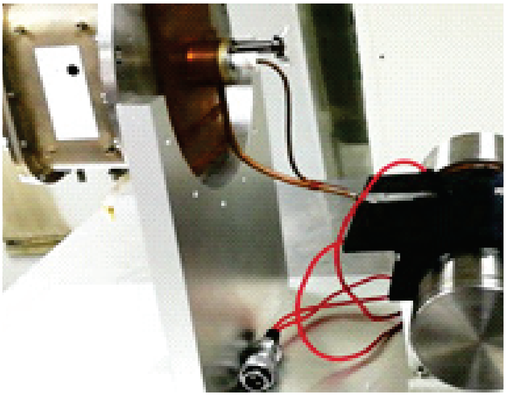

Figure 4. The photo of engineering model of PTC

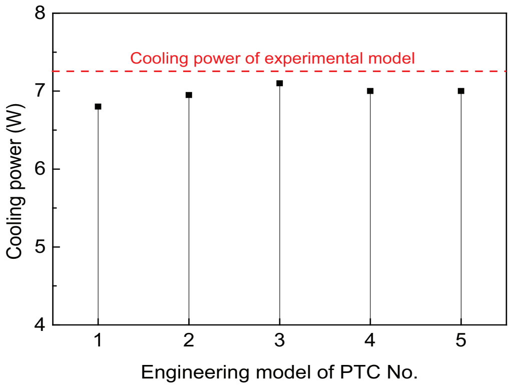

Figure 5. The cooling performance of five engineering model of PTC

CONCLUSIONS

In this paper, a high efficiency coaxial PTC was developed for infrared sensors. Based on the cryocooler requirements for infrared sensor applications, a coaxial PTC model was built using Sage modeling The regenerator length was first optimized using Sage. Subsequently, some experiments were performed to optimize the length of cold-finger. Analysis and experimental results confirmed that the optimal frequency of the PTC increased with decreasing cold-finger length. After experimental optimizations, the experimental PTC model achieved a typical cooling power of 5W at 60K with an electric power of 160W. Currently, five engineering models of PTC have been manufactured; the experimental results show that all of the engineering models have almost the same cooling ability as the experimental model. This indicates that our design and fabrication are relatively mature. Other engineering works of this kind of PTC are still underway.

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REFERENCES

1. Zia, J., "A pulse tube cryocooler with 300W refrigeration at 80K and an operating efficiency of 19% Carnot," *Cryocoolers*, vol.14 (2007), pp.141-147.
2. Hu, J., Zhang, L., Zhu, J., et al. "A high-efficiency coaxial pulse tube cryocooler with 500 W cooling capacity at 80 K," *Cryogenics*, vol.62 (2014), pp.7-10.
3. Hu, J., Dai, W., Luo, E., et al. "Development of high efficiency Stirling-type pulse tube cryocoolers," *Cryogenics*, vol.50 (2010), pp.603-607.
4. Dang, H., "High-capacity 60 K single-stage coaxial pulse tube cryocoolers," *Cryogenics*, vol.52 (2012), pp.205-211.
5. Zhang, A., Wu, Y., Liu, S., et al. "Simulation and Experimental Study of a 6W@ 60K PTR," *Journal of Engineering Thermophysics*, vol.36 (2015), pp.945-948. In Chinese.
6. Liu, X., Quan, J., Liu, Y., et al. "Design and optimization on 60K high capacity coaxial pulse tube cryocooler," *Journal of Engineering Thermophysics*, vol.9 (2014), pp.1698-1701. In Chinese.
7. Wang, N., Zhao, M., Ou, Y., et al. "A high efficiency coaxial pulse tube cryocooler operating at 60K," *Journal of Engineering Thermophysics*, (2018).