A Lightweight 6W/80K Pulse Tube Cryocooler

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ABSTRACT

For the demands of higher cooling power, lower mass and higher efficiency of the pulse tube cryocooler (PTC) used in space applications, a lightweight single-stage coaxial 6W/80K PTC was successfully developed by the Key Laboratory of Technology on Space Energy Conversion, CAS. In this paper, the details of the cooling performance are presented at different input powers ranging from 50W to 150W. Experimental results show that this PTC typical provides a cooling power over 6W at 80K with an electric power of 150W. By means of increasing the operating frequency, the weight of PTC was decreased significantly. At present, the optimal frequency is 78Hz, and the total PTC weight is only 2.3kg. The specific mass (cooling capacity/mass) is 2.6W/kg.

INTRODUCTION

In recent years, there is an urgent requirement for high efficiency and compact cryocoolers, especially in the field of high-capacity cryocoolers. However, the PTCs become more cumbersome with the increase of cooling capacity. [1] Because a space payload is space and mass limited, it is difficult to carry such a heavy and large refrigerator into the space. [2] Therefore, reducing the volume and weight of the high-capacity PTCs is an urgent matter.

Many efforts have been done to reduce the mass of PTCs. In 2009，NGST developed a micro cooler which weighs 857grams, it had a cooling power of 1.3W at 77K with an electric power of 50W.[3] In 2010, SITP designed a miniature coaxial pulse tube cryocooler for a space-borne infrared detector system. It weighs about 1.5kg and its operating frequency is about 70Hz. When the input power is 65W, the cooler can provide a cooling power of 1.6W at 90K. [4] In 2014, Lockheed Martin reported a micro PTC with high reliability. The micro PTC weight is 328 grams, including the 210 grams compressor. It has a cooling loads of 0.85W at 150K with 10W of power input.[5]

Our group has conducted the research on lightweight PTCs for years. In 2017, a 1.6kg lightweight PTC was built, and it could provide a large cooling power over 2W at 80K, the cooling temperature of the PTC can be reduced from room temperature to 80K within 2 minutes.[6] In 20017, a 72Hz single-stage coaxial PTC was also developed in our group, which can provide a cooling capacity up to 12W at 80K.[7]

For the above-mentioned micro PTCs, their cooling powers are still low, and their specific mass (cooling capacity/mass) are still high. Thus, there still is big potential to improve the compactness of the PTC. In this paper, based on the demands of a lightweight high capacity PTC used in space, we designed a coaxial PTC model using the Sage software, the regenerator length and diameter were optimized using this model. After that, some experiments were carried out to measure the operation performance of the PTC. At the end, the efficiency of the PTC is discussed in detail.

SIMULATION RESULTS

PTC Model

Figure 1 shows the entire SAGE PTC model. As shown in Figure 1, a PTC consists of a compressor, a connecting tube, a coaxial cold finger and a phase shifter. The compressor is a device that converts electrical power into PV power. The coaxial cold finger consumes PV power to obtain cooling capacity. The connecting tube is a transmission pipe for PV power, which is helpful for isolating the vibration. The phase shifter is used to adjust the phase angle between the mass flow and pressure wave. Figure 2 shows the SAGE model of a coaxial cold finger. The cold finger is composed of two heat exchangers, a regenerator, a pulse tube and two flow straighteners. The heat exchangers are finned-tube exchangers for sufficient convection heat transfer between gas and material. The coaxial regenerator is divided into two parts, one is filled with 500 mesh SSS (stainless steel screen), another is filled with 600 mesh SSS. The flow straighteners are used to reduce the impact of the jet flow.

Optimization of Regenerator

Based on the PTC model, some simulation works are carried out to obtain a high frequency and high efficiency cold finger. Figure 3 shows the simulation results for the variation in cooling power and COP versus the regenerator length. The results demonstrate that the curve of cooling power and COP have different trends. The maximum cooling power is obtained at the regenerator length of about 29mm, however, the max COP is obtained at the regenerator length of about 33mm. Taking into consideration both the COP and the cooling power, 31 mm is chosen as the optimal regenerator length.

When the regenerator length is set to 31mm, the regenerator diameter is optimized using the SAGE model. As shown in Figure 4, the curve of cooling power and COP also have a different trend with the variation of regenerator diameter. The PTC achieves the biggest cooling power when the

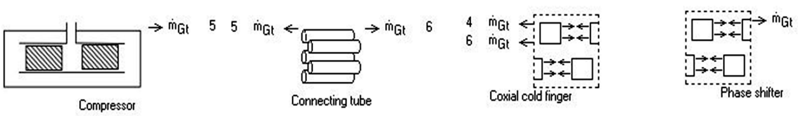

Figure 1. SAGE model of a PTC

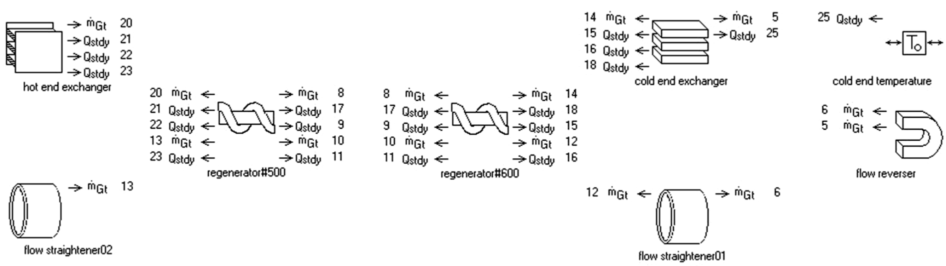

Figure 2. SAGE model of a cold-finger

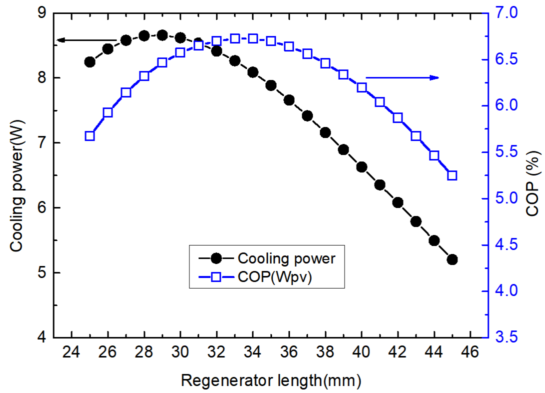

Figure 3. Optimization of the regenerator length

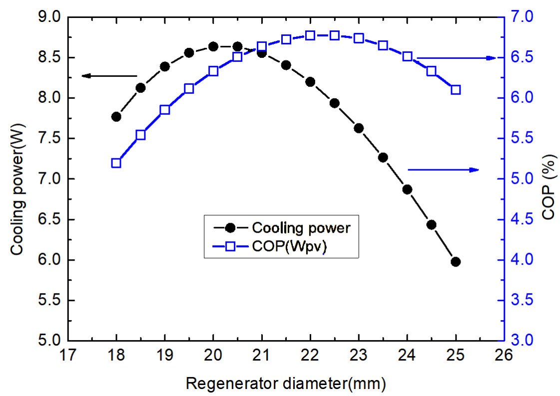

Figure 4. Optimization of the regenerator diameter

diameter of regenerator is about 20 mm, and the PTC achieves the highest COP when the diameter of regenerator is about 22 mm. Taking into consideration both the COP and the cooling power, 21 mm is chosen as the optimal regenerator diameter.

After simulation, the optimal parameters of main components are obtained. As labeled in Table 1, the length and diameter of regenerator are 31mm and 21mm, and the corresponding frequency is 80Hz. The regenerator is filled with 500 mesh and 600 mesh SSS. The connecting tube is 100 mm in length with an inner diameter of 3mm.

EXPERIMENTAL RESULTS

PTC Description

According to the optimization results, a lightweight cold finger was designed and fabricated. The cold finger was matched with a high-frequency miniature linear compressor, as displayed in Figure 5. The total weight of the PTC is only 2.3kg.

Cooling Map of the PTC

Some necessary experimental optimization works were carried out, and the cooling performance of the PTC was showed in Figure 6. As can be seen, the operating frequency is 78Hz, the charge pressure is up to 4.0MPa. The cooling capacity was measured with the input power of 50W, 100W

Table 1. Simulation results of the PTC

Components	Values
Length of REG	31mm
Diameter of REG	21mm
Frequency	80Hz
Hot temperature	300K
Mesh	#500&#600 stainless steel screen
Connecting tube	100mm long and an inner diameter of 3mm

Figure 5. Photo of the lightweight PTC

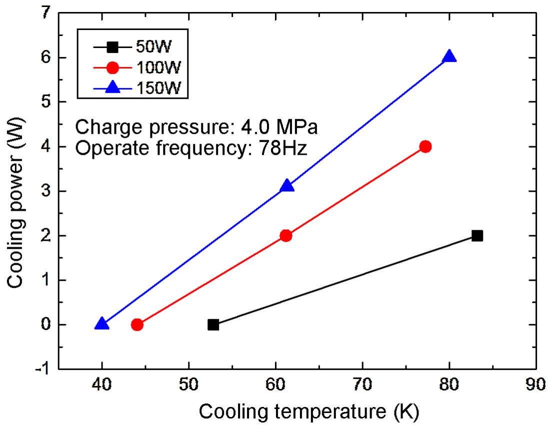

Figure 6. Cooling map of the PTC

and 150W. When the input power is 150W, the PTC is able to provide a maximum cooling power of 6W at 80K, and the specific mass of this lightweight PTC can reach 2.6W/kg.

The compressor and the cold finger do not match well because the small compressor is not tailored to the cold finger. Figure 7 shows the COP (P-ele) (cooling capacity/electricity) of the PTC relative to the input electrical power, the COP (P-pv) (cooling capacity/PV work) relative to the input

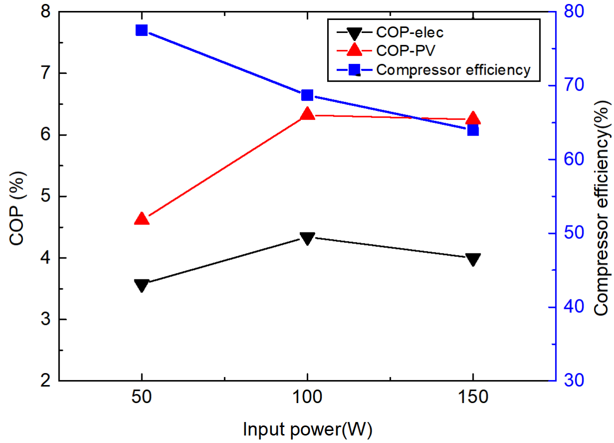

Figure 7. Experimental results of cooling performance with different hot temperature

PV power, and the efficiency of the compressor (PV power/ electric power). It can be seen from the figure that with an increase in the input electric power, all of the COP rises rapidly at first and then decreases slowly, and the PTC obtains the highest COP under the input power of 100W. However, the efficiency of the compressor is always reduced as the input electric power is increased. When the input electric power is 50W, the compressor efficiency is 78%; when the input electric power is 150W, the compressor efficiency is only 64%. It means that when the input electric power is high, the matching between the cold finger and the compressor is more unreasonable, which seriously limits the improvement of PTC efficiency. Next, the compressor will be optimized to improve the coupling efficiency, and future work will be done to improve the efficiency of the lightweight PTC.

CONCLUSIONS

To reduce the weight of the high capacity pulse tube cryocooler, a coaxial PTC model was built with SAGE, and the regenerator length and diameter were optimized. Based on the simulation results, a cold finger was manufactured and tested. The experimental results show that the operating frequency is 78Hz, and the lightweight PTC can provide a cooling power of 6W/80K with a mass of 2.3kg, the corresponding specific mass is 2.6W/kg. In the future, more studies will be carried out to improve the COP of the PTC.

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