Design on a Two-Stage Stirling/Pulse Tube Hybrid Cryocooler

C.H Yin, Z.H Gan, B. Wang, Y.X. Guo

Institute of Refrigeration and Cryogenics, Zhejiang University
Hangzhou 310027, P.R. China
Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province
Hangzhou 310027, P.R. China

ABSTRACT

In the field of military and aerospace, there are strict requirements for cryocoolers, such as high efficiency, compactness, light weight, high reliability, long life and low vibration limits. At present, most mechanical cryocoolers which can be applied in space are Stirling cryocoolers and Stirling type pulse tube cryocoolers. Two-stage cryocoolers are sought-after for aerospace applications, since the performance of single-stage cryocoolers is limited below 35 K, especially at 20 K. Compared with two-stage Stirling cryocoolers, Stirling/pulse tube hybrid cryocoolers eliminate the moving parts of the second stage, which leads to longer life. Moreover, hybrid cryocoolers can achieve higher pressure ratios and efficiency in their regenerator due to a better match in charging pressure between stages. In this study, we designed a two-stage Stirling/pulse tube hybrid cryocooler at 20 K with low temperature inertance tubes and a surge volume to adjust the phase difference. We simulated the performance of the designed cryocooler using the Sage code, and proved that the as-designed cryocooler can provide 0.54 W cooling power at 20 K with 180 W electrical power input. In addition, the effects of the phase difference, mass flow, and pressure ratio in the displacer are also discussed.

INTRODUCTION

Regenerative cryocoolers have been widely applied in aerospace and other fields due to their promising features, such as high efficiency, compactness, light weight, high reliability, long life and low vibration. At 80 K, single-stage Stirling cryocoolers and Stirling type pulse tube cryocoolers predominate. However, below 35K, especially near 20K, the performance of single-stage cryocooler is limited and multi stage cryocoolers are required.

Compared with two-stage Stirling cryocoolers, Stirling/pulse tube hybrid cryocoolers eliminate the moving parts of the second stage, which leads to longer life. However, Stirling type pulse tube cryocoolers require a larger gas volume that must be cyclically pressurized and depressurized. It is known that the larger gas volume increases the gas mass flow and reduces the efficiency of the regenerator[1]; moreover, Stirling type PTCs need higher charge pressure to approach their optimal phase condition, and this increases the pressure drop and reduces the efficiency of the system.

Stirling/pulse tube hybrid cryocoolers evade the wear and tear of Stirling cryocoolers and the low efficiency of Stirling type pulse tube cryocoolers, taking advantage of the best of these two kinds of cryocoolers to achieve high efficiency and long life.

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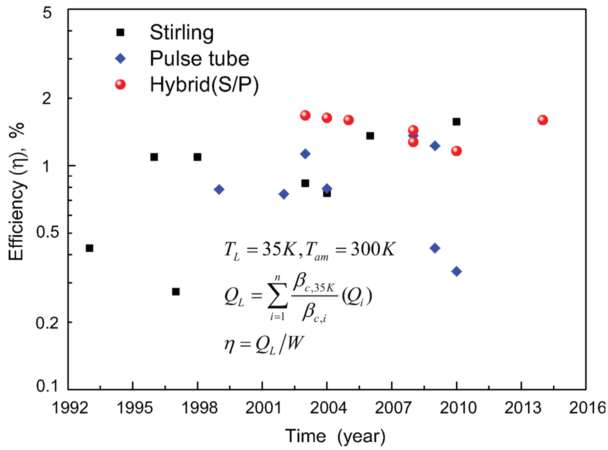

Figure 1. Comparison of the efficiency of Stirling cryocoolers at 35 K region.

We collected efficiency data for Stirling/pulse tube hybrid cryocoolers, Stirling cryocoolers and Stirling type pulse tube cryocoolers between 1992-2014, as shown in Figure 1. From the plot, it is apparent that the efficiency of hybrid cryocoolers is higher than those of others.

Besides the high efficiency and long life, Stirling/pulse tube hybrid cryocoolers also exhibit a better pressure-matching and higher pressure ratio at the cold end. For high frequency Stirling type pulse tube cryocoolers, the different temperature ranges correspond to different best charge pressure. For example, the best charging pressure for Stirling type PTC in the 80 K region is 2-2.5 MPa, while in the 20 K region it is 1.0 to 1.5 MPa. Therefore, for multistage gas coupling cryocoolers, it is challenging to optimize the charging pressure at different temperature regions simultaneously. In order to guarantee the performance in the low temperature region, cryocoolers must sacrifice efficiency in the 80 K region. For multistage cryocoolers with thermal coupling, they can use an independent compressor system to achieve the maximum efficiency of each stage. While the system becomes complex, the charging pressure of the Stirling cryocooler should be between 1 to 2 MPa, so that it can match well with the secondary Stirling type pulse tube cryocooler's charging pressure preference. A good pressure match on different stages can reduce the pressure drop in the regenerator and raise the pressure ratio at the cold end. This means that Stirling/pulse tube hybrid cryocoolers have the potential to achieve better performance than multistage Stirling type pulse tube cryocoolers.

The Raytheon Company first proposed the concept of a Stirling/pulse tube hybrid cryocooler and designed a prototype in June 2000. The prototype adopted a U structure for the second stage and achieved 2.2 W at 80 K and 0.5 W at 35 K.[2]

The Raytheon Company improved the cryocooler in 2002 and formed the RSP2 model which increased performance up to 1W at 35K plus 7W at 100 K for a drive motor whose input power is less than 170 W. The total mass is less than 7 kg. [3]

In 2005, the Raytheon Company redesigned the gas transmission route and further improved the performance to 1.1 W at 60 K and 4.3 W at 110 K for a PV power consumption of 72 W.[4]

In 2008, the Raytheon Company developed a Dual-Use Cryocooler (DUC) with a coaxial structure and compact components. At the same time, Raytheon continuously improved the HC-RSP2 models, and developed MC-RSP2 models. The performance of the MC-RSP2 is 2.7 W at 58 K and 6.7 W at 110 K with a PV power consumption of 210 W.[5]

In 2009, the Raytheon Company further improved the HC - RSP2 and MC - RSP2 coolers to make their performance better. Test results were: 2.6 W at 35 K and 16.2 W at 85 K with an electric power consumption of 513 W for HC-RSP2, and 2.4 W at 58 K and 6.1 W at 110 K the for MC-RSP2 design with an electric power consumption of 166 W. The initial design requirements were basically met. What's more, it was determined that the HC-RSP2 could provide 0.38 W of cooling capacity at 12 K, and the lowest refrigerating temperature was below 10 K.[5]

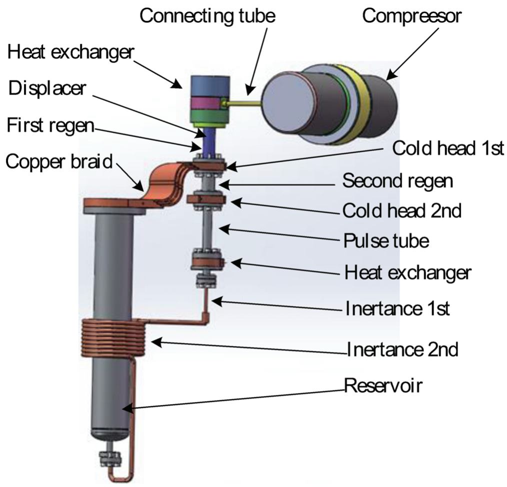

Figure 2. Design sketch of the Stirling/pulse tube hybrid cryocooler.

In 2010, in order to explore the application of 4-10 K region, Raytheon Company designed a cryocooler LT-RSP2, based on the HC-RSP2 design, which was focused on low-temperature cryogenic applications. The design goal for LT-RSP2 was to achieve 1 W at 12 K and 5W at 60K with an input power of 500 W; the lowest cooling temperature was close to 9 K.[6]

In 2013, the Raytheon Company reworked the DUC system designed in 2008. Using an advanced regenerator they streamlined the assembly, and the efficiency of the thermodynamics was improved as a result; the resulting Carnot efficiency for the DUC system was increased by 2%.[7]

DESIGN FOR THE STIRLING/PULSE TUBE HYBRID CRYOCOOLER

In light of the above-mentioned advantages, a two-stage hybrid cryocooler was designed. Figure 2 depicts the cryocooler's structure. The first stage is the POLAR SC-7 COM Stirling cryocooler, and the second stage is a pulse tube hybrid cryocooler. The structure is gas coupled. A low temperature inertance tube and surge volume were adopted to adjust the phase difference. The copper surge volume is heat sunk to the cold head of the first stage through a copper braid.

We simulated the performance of the as-designed PTC using Sage. The performance of the POLAR SC-7 COM Stirling cryocooler is 6 W at 77 K with an input power of 180 W. Based on the experiments and simulation, the cooler can provide a cooling capacity of 9.2 W at 104 K when the input electric power is 180 W, frequency is 37 Hz, and pressure is 1.7 MPa.

The temperatures at different positions in the cryocooler are shown in Figure 3. For the first stage, the temperature of hot end is about 310 K, while the temperature of cold end is about 104 K. It provides 9.2 W cooling capacity. For the second stage, the temperature of the cold end of regenerator is about 20 K. The hot end of pulse tube surge volume and inertance tubes are connected together, thus their temperatures are the same 104 K.

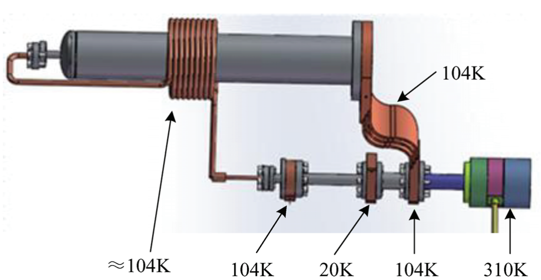

Figure 3. The temperature distribution in the cryocooler

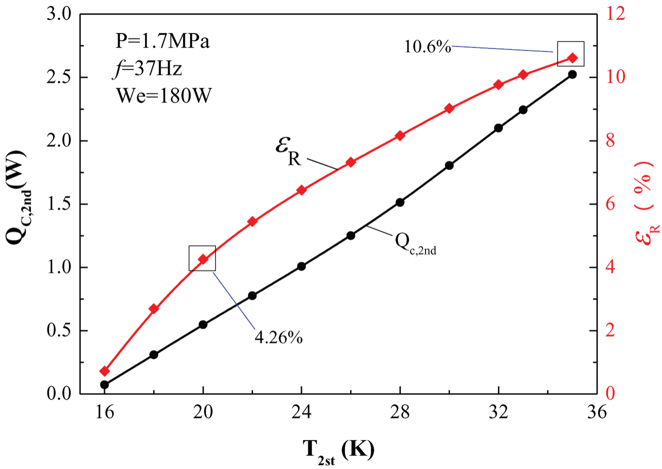

Figure 4. The efficiency of the designed hybrid cryocooler.

We simulated the refrigerating performance of the proposed hybrid cryocooler, and plotted the second stage cooling power and efficiency versus cold head temperature, as shown in Figure 4. The cryocooler can reach 0.54 W cooling capacity with a relative Carnot efficiency of 4.26% at 20 K. When the refrigerating temperature increases to 35 K, the cooling capacity is 2.52 W, and the relative Carnot efficiency is 10.6%.

THE KEY PARAMETERS ANALYSIS

The key operating parameters of the Stirling/pulse tube hybrid cryocooler are analyzed as follows:

Dependence of the First-stage Temperature on Pressure and Frequency

Operating parameters such as frequency, pressure and input power have significant effects on the cryocooler performance. As seen from the Figure 5, when the input power is 180 W and the frequency is 37 Hz, the cooling capacity of the second stage (20K) increases first and then decreases as pressure increases. The best pressure is 1.7 MPa, which corresponds to the cooling power of 0.54 W. In addition, with the increasing pressure, the acoustic power of expansion chamber entrance increases. That is to say, increasing of cooling capacity of the first stage leads to reduced temperature at its cold head, as shown in Figure 6.

Similarly, when the input power is 180 W and the pressure is 1.7 MPa, the secondary cooling capacity increases first and then reduces with increasing frequency. The optimal frequency is 37-38 Hz,

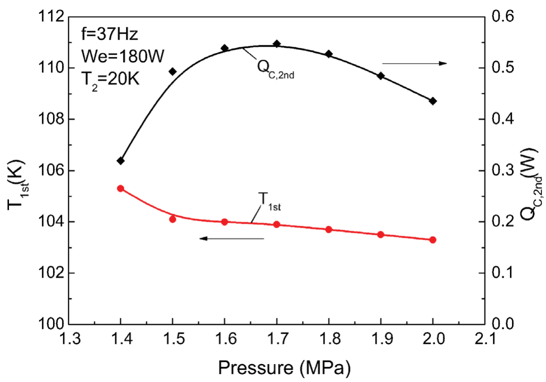

Figure 5. Graph of secondary cooling capacity and the temperature of cold head for the first stage when pressure changes.

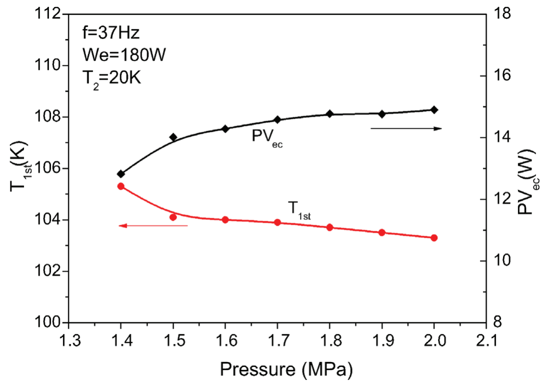

Figure 6. Graph of the temperature of cold head for the first stage and the acoustic power of expansion chamber entrance.

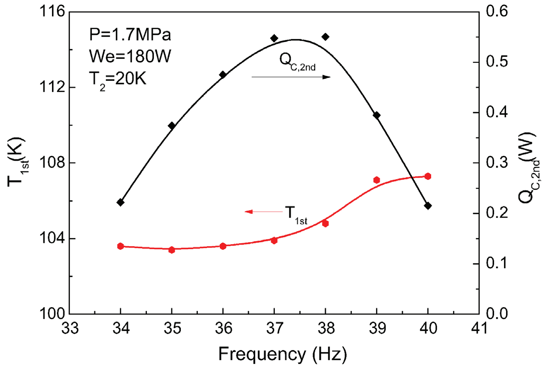

Figure 7. Graph of secondary cooling capacity and the temperature of cold head for the first stage when frequency changes.

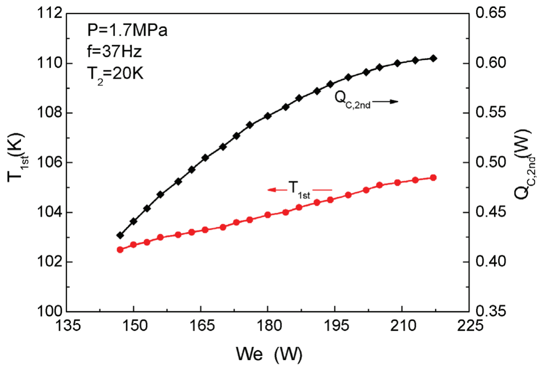

Figure 8. Graph of secondary cooling capacity and the temperature of cold head for the first stage when input power changes.

and correspondingly, the cooling capacity is 0.54 W. In addition, with the increasing frequency, the first stage's refrigerating temperature increases as shown in Figure 7. This is because the effect of frequency on the thermal efficiency of the regenerator is significant. A frequency which is too high or too low will cause the efficiency drops, leading to a drop of pressure.

Figure 8 shows the dependence of the secondary cooling capacity and the temperature of the cold head for the first stage on input power. Increasing the input power, the first stage's refrigerating

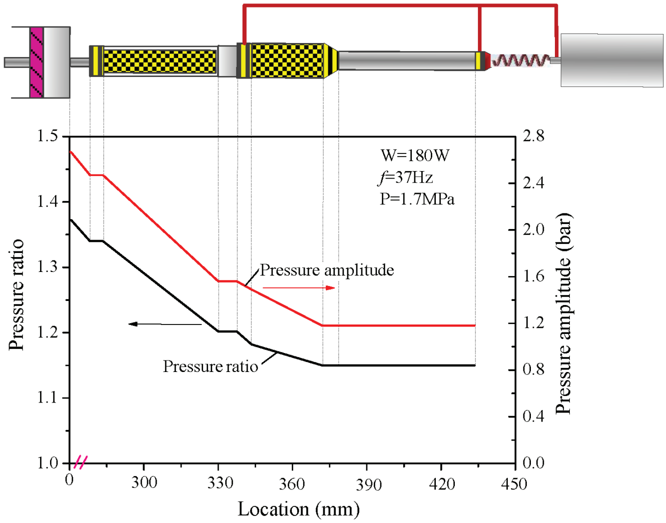

Figure 9. Changes of pressure ratio and pressure amplitude in the cryocooler.

temperature and secondary cooling capacity also increase. What's more, the first stage's refrigerating temperature increases almost linearly with the input power, but the secondary cooling capacity increases more and more slowly. When the input power increases to a certain extent, the secondary cooling capacity tends to be stable.

The Variance of Pressure Ratio and Acoustic Power in the As-designed PTC

In order to analyze the changes of parameters, such as pressure ratio and mass flow, the structure of this cryocooler is simplified. As shown in Figure 9, from left to right, the components are compressor, connecting tube, heat exchanger for the hot end, the first regenerator, expansion chamber, the intermediate heat exchanger, secondary regenerator, heat exchanger for the cold end, pulse tube, heat exchanger for the hot end of pulse tube, inertance tubes, surge volume and thermal bridge connecting secondary cold end and inertance tubes.

In Figure 9, the changes of pressure ratio and pressure amplitude are synchronized. Pressure drop is mainly caused by the connecting tube, the first regenerator and the secondary regenerator. This is because the regenerators are filled with wire mesh, which increases the flow resistance. Although there is no wire mesh compared with the heat exchanger and regenerators, the connecting tube is long and its diameter is small, which causes a significant pressure drop.

As mentioned above, the pressure drop happens in the connecting tube and regenerators, which can attenuate the acoustic power correspondingly. Figure 10 shows the variance of acoustic power within each component in the cryocooler. Along the connecting tube, heat exchanger for the hot end and the first regenerator, acoustic power decreases from 98 W to around 15 W until the expansion chamber, and continues to decrease to 4.3 W in the second regenerator again. In the pulse tube, acoustic power stays stable.

The Changes of Phase Difference and Mass Flow

As shown in Figure 11, the mass flow decreases significantly in the hot end heat exchanger, increases between the first and secondary state regenerators, and decreases in the pulse tube again. This is because the temperature in the hot end heat exchanger rises, which decreases the density of helium. Correspondingly, in the first and secondary regenerator, the temperature reduces, which makes the density of helium increase. In the pulse tube, temperature rises from around 20 K to 104 K, which makes the density of helium decrease again. In the cryocooler, the phase difference changes greatly at the hot end heat exchanger: from 28 ° to nearly 1°. In the first regenerator, it changes from 1° to -27 °.

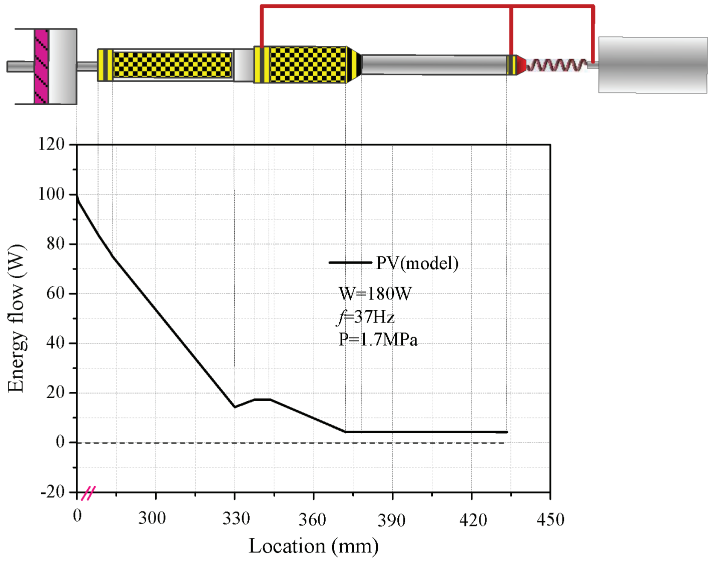

Figure 10. Changes in acoustic power within each component in the cryocooler.

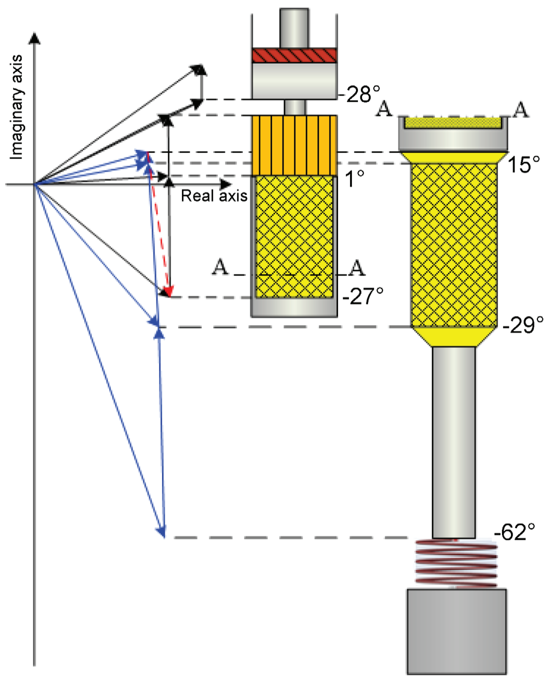

Figure 11. Changes of mass flow and phasor in the cryocooler.

Helium is shunted between the first and the secondary stage. As a result, the phase difference at the hot end of secondary regenerator is about 15° and at the cold end is - 29°. The structure of low temperature inertance tubes and surge volume lead to the phasor at the hot end of pulse tube reaching -62°.

CONCLUSION

In this paper, we compared the performance of a two-stage Stirling cryocooler, Stirling PTC and Stirling/pulse tube hybrid cryocooler. We also proposed a model for a two-stage gas coupled Stirling/pulse tube hybrid cryocooler. We simulated the performance of the as-designed cryocooler by studying the variance of operating parameters, such as the pressure ratio, acoustic power, mass flow and phase difference. The proposed two-stage Stirling/pulse tube hybrid cryocooler can provide 0.54 W at 20 K with 180 W input power. The experiments will be carried out soon.

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