Numerical analysis and experimental research of a 2W/35 K Stirling-type pulse tube cryocooler

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Abstract. Cooling to the temperature of liquid nitrogen to liquid hydrogen is a necessary working prerequisite for some infrared detectors. The development of compact and efficient miniature cryocoolers is of great significance for the space application of the detectors. The pulse tube cryocooler driven by a dual-opposed linear compressor is prospective in space applications due to the advantages of no low-temperature moving parts, compact structure, and high reliability. In this paper, a 2W/35K Stirling-type pulse tube cryocooler with a single-stage structure has been designed and tested. The influences of structural parameters of the phase shifters such as inertance tube, as well as the operating parameters such as operating frequency and charging pressure, on the cooling performance were investigated through numerical calculations and experiments.

1. Introduction
Owing to the advantages of no low-temperature moving parts, compact structure, high reliability, and long life, Stirling-type pulse tube cryocoolers are promising candidates for ground experiments and space applications. At present, Stirling-type pulse tube cryocoolers working in the liquid nitrogen temperature zone have been commercialized, and it is usually a single-stage structure [1-4]. In order to obtain a lower temperature, it is usually necessary to use a multi-stage structure [5-9]. This paper has developed a Stirling-type pulse tube cryocooler that works at 35 K, which also adopts a single-stage structure. The phase shifters are inertance tubes and a gas reservoir, instead of the combination of multi-bypass and double inlet used in the previous 20 K Stirling-type pulse tube cryocooler [10-12], which is beneficial to simplify the refrigeration process.

2. Calculation results of the cryocooler
2.1. The influence of structural parameters on the performance of the cryocooler
The schematic and the 3D structure diagram of the developed Stirling-type pulse tube cryocooler are shown in figure 1 and figure 2, respectively. In order to achieve a compact structure and facilitate flexible thermal coupling connection with the load, the single-stage cryocooler adopts a coaxial arrangement.
The commercial numerical calculation software SAGE 11.0 was used to carry out the numerical calculation. The main structural parameters are listed in Table 1. The inertance tube adopts a three-stage structure with different inner diameters.

**Table 1. The main structural parameters of the single-stage Stirling-type pulse tube cryocooler.**

| Parameter                              | Value                                    |
|----------------------------------------|------------------------------------------|
| The length of the regenerator          | 90.5 mm                                  |
| The outer diameter of the regenerator  | 26.4 mm                                  |
| The length of the pulse tube           | 107 mm                                   |
| Regenerator cold storage packing       | 400# Stainless steel wire mesh           |
| Inertance tube                         | Φ2mm+Φ3mm+Φ4mm                            |

For the first section of the inertance tube with an inner diameter of 2 mm, the influence of its length on the cooling performance is analyzed, as shown in figure 3. The piston stroke of the compressor is 5.2mm, the operating frequency is 32 Hz, and the charging pressure is 3 MPa. The cooling capacity at 35 K rises firstly and then declines with the increase in the length. When the length is 1 m, the maximum cooling capacity is 2.1 W.
2.2. The influence of operating parameters on the performance of the cryocooler

In addition to the structural parameters, the operating parameters of the cryocooler also have an important impact on the cooling performance. Among them, the operating frequency not only affects the output power characteristics of the compressor, but also affects the mass and heat transfer between the cold storage material and the working fluid. Taking the operating frequency as a variable, the influence on the no-load temperature and the cooling capacity at 35 K of the cryocooler is shown in figure 4. As the frequency increases, the no-load temperature first decreases and then increases, and the cooling capacity at 35 K first increases and then decreases. The minimum no-load temperature and the maximum cooling capacity at 35 K corresponding to the optimal frequency are slightly different, which are 38 Hz and 36 Hz, respectively.

The influence of the input power on the no-load temperature and the cooling capacity at 35 K is shown in figure 5. The adjustment of PV power is realized by controlling the piston displacement in the numerical calculation. It can be seen from figure 5 that about 230 W of PV power is required to obtain a cooling capacity of 2W/35K.
3. Experimental results and discussion

Based on the numerical calculations, a prototype was designed and manufactured. Relevant parameters such as the regenerator and phase shifters of the cryocooler were optimized by experiments, and the influence of operating parameters such as frequency and input power on the cooling performance was investigated in detail. When the charge pressure is 3 MPa and the input electrical power of the compressor is maintained at 300 W, the influence of the operating frequency on the no-load temperature and the cooling capacity at 35 K of the cryocooler is shown in figure 6 and figure 7, respectively. It can be seen from the figures that the experimental results are in good agreement with the trends of the calculated results. The optimal frequency for the no-load temperature is 33 Hz with the no-load temperature of 28.73 K. The optimal frequency for the cooling capacity at 35 K is 32 Hz, and the cooling capacity obtained is 1.53 W.

Figure 5. The influence of PV power on the cooling performance.

Figure 6. The experimental influence of operating frequency on the no-load temperature of the cryocooler.
The compressor input electrical power is used as a variable, and the experimental results of the no-load temperature and the cooling capacity at 35 K of the Stirling-type pulse tube cryocooler are shown in figure 8 and figure 9, respectively. It can be seen from the figures that both the no-load temperature and the cooling power at 35 K change linearly with the change of the compressor input electrical power. When the input power is 325 W, 1.8 W cooling capacity at 35 K is obtained. Compared with the statistical data of ter Brake et al. [13], the efficiency of the cryocooler is at the same level as the performance of the existing Stirling cryocoolers with higher efficiency. However, there is a slight deviation between the experimental results of the prototype and the calculation results of the model, which may be caused by the low efficiency of the compressor. Specifically, the calculated input PV power is about 220 W, so the compressor efficiency is 0.68. In the next step, we will continue to study the coupling characteristics of the compressor and the cold tip to further improve the cooling efficiency.
Figure 9. The experimental influence of input electrical power on the cooling power at 35 K.

4. Conclusion
A 35K/2W Stirling-type pulse tube cryocooler was designed and tested. The influences of structural parameters of the phase shifters such as inertance tube, as well as the operating parameters such as operating frequency and charging pressure, on the cooling performance were investigated through numerical calculations and experiments. At present, a cooling power of 1.8W/35K has been achieved with an input electrical power of 325 W. In the next step, we will continue to study the coupling characteristics of the compressor and the cold tip to further improve the cooling efficiency.

5. References
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