Design and test of the Stirling-type pulse tube cryocooler

Yong-Ju Hong, Junseok Ko, Hyo-Bong Kim, Han-Kil Yeom, Sehwan In and Seong-Je Park
Korea Institute of Machinery & Materials, Daejeon, 34103, Korea

Abstract. Stirling type pulse tube cryocoolers are very attractive for cooling of diverse application because it has it has several inherent advantages such as no moving part in the cold end, low manufacturing cost and long operation life. To develop the Stirling-type pulse tube cryocooler, we need to design a linear compressor to drive the pulse tube cryocooler. A moving magnet type linear motor of dual-opposed configuration is designed and fabricated, and this compressor could be operated with the electric power of 100 W and the frequency up to 60 Hz. A single stage coaxial type pulse tube cold finger aiming at over 1.5 W at 80K is built and tested with the linear compressor. Experimental investigations have been conducted to evaluate their performance characteristics with respect to several parameters such as the phase shifter, the charging pressure and the operating frequency of the linear compressor.

1. Introduction
Stirling type pulse tube cryocoolers are very attractive for cooling of diverse application because it has it has several inherent advantages such as no moving part in the cold end, low manufacturing cost and long operation life.

The coaxial pulse tube cold finger configuration, which has the similar appearance to the Stirling cryocooler, has been widely used for the cooling of the infrared detectors [1,2].

In the pulse tube cryocooler, the phase shifting mechanism performs the function of maintaining the appropriate phase relationships between the pressure wave and the flow. Proper phase relationship must exist in regenerator to operate optimally. An inertance tube is effectively used in high frequency pulse tube cryocooler [3,4].

A single inertance tube with constant inner diameter often has great difficulty in obtaining the desired phase relationship. Therefore, the double-segmented inertance tube with different diameters and lengths, respectively, has been used to achieve a satisfactory phase shift within the acceptable tube length [5,6].

The optimal match between the pulse tube cold finger and the linear compressor plays a vital role in optimizing the compressor efficiency and in improving cooling performance [7].

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Table 1. Design specification of the pulse tube cryocooler

| Parameter                              | Values | Unit |
|----------------------------------------|--------|------|
| Operating temperature                 | 80     | K    |
| Operating frequency                    | 50     | Hz   |
| Diameter and length of compressor     | 100 / 200 | mm   |
| Max. swept vol. of compressor          | 5.6    | cc   |
| Thrust constant of motor               | 10.0   | N/A  |
| Diameter of cold finger               | 19     | mm   |
| Length of pulse tube                   | 182    | mm   |
| Regenerator                           | #400 stainless steel screens |
| Porosity of regenerator               | 0.653  |      |
| Reservoir volume                      | 150    | cc   |

2. Design and optimization of the pulse tube cryocooler

The pulse tube cryocooler is addressed as the split arrangement because the pulse tube cold finger is connected with a linear compressor through a connecting tube. The linear compressor adopts the dual-opposed configuration to minimize the self-induced vibration. The pulse tube cold finger adopts the coaxial configuration. The inertance tube, which consists of two sections with different inner diameter and length, is optimized at 80 K to obtain the desired cooling capacity. The inertance tube is coiled in the reservoir. Main parameters of the pulse tube cryocooler are shown in Table 1.

In this study, Sage software [8] is employed to simulate the performance of the pulse tube cryocooler. Figure 1 shows the root level of Sage model of the pulse tube cryocooler. A parameter for optimization is a length of double-segmented inertance tube of the pulse tube cryocooler. During the optimization, inner diameters of the first (IT1) and second (IT2) segments are 2.0 mm and 3.56 mm, respectively.

Figure 2 shows simulation results for the performance of the pulse tube cryocooler from 3.5 m, 4.0 m, 4.5 m. The total length of the inertance tube, respectively. The operating frequency and the charging pressure are 50 Hz and 2,500 kPa. The result shows increases in the PV power with increasing the length of the first segment of the inertance tube. Also, there appear to be increases in the PV power with increasing the total length of the inertance tube. As shown in Figure 2 (b), there exists an optimal length of IT1 for each total length of the inertance tube to achieve the maximum cooling capacity. The optimal cooling capacity occurs at about the length of IT1 of 1.6 m for the total length of 4.5 m. And results show a cooling capacity of 1.93 W with the PV power of 64 W at the length of IT1 of 1.6 m for the total length of 4.5 m.

![Figure 1](image-url)

Figure 1. Model of Sage with a double-segmented inertance tube of the pulse tube cryocooler.
Figure 2. Simulation results at 80K with the length of inerance tube.

Figure 3. Cooling capacity and pressure ratio with the PV work of the compressor.

Simulations are performed for the operating frequency of 50 Hz, the charging pressure of 2,500 kPa, the total length of inerance tube of 4.5 m, and the length of IT1 of 1.8 m. As shown in Figure 3, the pressure ratio increases as the PV power of the compressor increases. The increase in the pressure ratio causes an increase in the cooling capacity.

3. Performance of the pulse tube cryocooler
The schematic diagram of the experimental setup is shown on Figure 4. The pulse tube cryocooler consists of the compressor, the coaxial pulse tube cold finger, and the connecting tube. A power supply is used to regulate the input power, a pressure transducer is placed at the connecting tube to monitor the dynamic pressure and phase angle. Also, the input current is measured for the reference of the phase angle. The cold end temperature is monitored by temperature sensor, and the heat load is provided by the heater. The power meter is used to acquire the cooling capacity and power consumption.

Figure 5 shows the cooldown characteristics of the pulse tube cryocooler. The operating frequency and charging pressure are 50 Hz and 2.6 MPa. During cooldown, the input power is gradually increased. The amplitude of the pressure decreases with decreasing cold end temperature. On the other hand, the power consumption increases. The pulse tube cryocooler get down to 80 K within 10 minute. The no load temperature is 61.1 K with the power consumption of 89.3 W.

Figure 6 show the cooling capacity at 80 K with the variation of the power consumption. Results show a cooling capacity of 1.79 W with the power consumption of 100 W. The cooling capacity
increases from 0 W to 1.79 W with the power consumption changing from 43 W to 100 W and the pressure ratio changing from 1.155 to 1.262.

**Figure 4.** Schematic diagram of the experimental setup.

**Figure 5.** Cool-down characteristics of the pulse tube cryocooler.

**Figure 6.** Cooling capacity vs. power consumption.
Figure 7. Performance of the pulse tube cryocooler in different operational frequency. The charging pressure and the cold end temperature are 2.5 MPa and 80 K. In an operating frequency ranging from 46 Hz to 54 Hz, the pressure ratio is proportional to the power consumption. The phase shift between pressure and current decreases from 126.6 degree to 97.6 degree with the operating frequency changing from 46 Hz to 54 Hz. The minimum values of the power consumption in the given cooling capacity are achieved at 50 Hz.

Figure 8. Performance of the pulse tube cryocooler in different charging pressures.
Figure 8 shows performances of the pulse tube cryocooler in different charging pressures. The operating frequency and the cold end temperature are 50 Hz and 80 K. At given power consumption, the pressure ratio decreases when the charging pressure increases from 2200 kPa to 2800 kPa. The phase angle of the pressure increases as the charging pressure increases. The magnitude of change in the phase angle of the pressure is smaller than in the variation of the operating frequency.

Figure 9 shows the cooling capacity and the power consumption in different charging pressure at the given input voltage. The operating frequency is 50 Hz. The no load temperature of the pulse tube cryocooler is about 61 K. Variations of the cooling capacity at 80 K with the charging pressure does not occur largely. The power consumption of the charging pressure of 2200 kPa is higher than other cases with the difference of 3 W. As the temperature change from 61 K to 80 K, the power consumption of the charging pressure of 2800 kPa varies from 88.9 W to 85.5 W.

4. Summary

In this study, we developed a single stage pulse tube cryocooler, which consist of the moving magnet type linear compressor and the coaxial type pulse tube cold finger, for the cooling of the infrared detector. The pulse tube cryocooler is capable of providing 1.79 W of cooling capacity at 80 K with 100 W power consumption. The pulse tube cool from ambient temperature to 80 K in less than 10 minute.

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