

## Recent Development Status of Stirling Type Pulse Tube Cryocooler for HTS

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**Abstract.** Sumitomo Heavy Industries, Ltd. (SHI) has been developing a high power stirling type pulse tube cryocooler. For the purpose of cooling high-temperature superconductor (HTS) devices, such as superconductor motor, SMES and current fault limiter, requested specifications from the devices to a cryocooler are compact size, light weight, high efficiency and high reliability. Especially, the cryocooler must be demanded COP > 0.1 in the efficiency. The experimental results of prototype pulse tube cryocooler were reported in June 2012 [1]. For an In-line type expander, the cooling capacity was 210 W at 77 K and the minimum temperature was 37 K when the compressor input power was 3.8 kW and the operating frequency was 49 Hz. Accordingly, COP was about 0.055. Moreover, for miniaturization a U type expander was tested and the performance is about 10 % less than that of an In-line type expander. After that, we have estimated that the cooling performance is influenced by the environment such as the effect of the pulse-tube inclination, the temperature and the flowing quantity of cooling water. The detailed results are reported in this paper.

### 1. Introduction

Recently, technical innovation of HTS devices *at al.* has brought about the necessity of high efficiency cryocoolers, and pulse tube cryocoolers with 100~1000 W at 77 K cooling capacity have been developed for HTS applications. In 2004, J. H. Zia et al. reported a commercial prototype Stirling type pulse tube cryocooler (SPTC) with 200 W cooling capacity as civilian equipment for HTS electronics applications [2]. For the purpose of cooling HTS and semiconductor sensor, a small size Stirling cryocooler had been developed. But it became a problem of the reliability of cryocooler to be decreased a cooling capacity by a wear of the expander piston seal when it drove for a long time. Pulse tube cryocoolers are more attractive of high reliability than with other regenerative cryocoolers (e.g., GM and Stirling cryocoolers), because of having no moving parts in the expander. SHI has been developing a prototype high power SPTC to satisfy the demand specification from the device to the cryocooler, smaller lightweight, the high efficiency and high reliability and the experimental results were reported in June 2012[1]. The expander of cryocooler was an In-line type and the cooling capacity was 210 W at 77 K when the compressor input power was 3.8 kW at the operating frequency of 49 Hz, a compressor efficiency of 74 % and COP 0.055. In regard to the arrangement of the cryocooler system, a U type is more compact and is more convenient for this application and the performance was 191 W at 77 K, with the lowest temperature at 44 K. The performance decreased about 9.1 % compared to that of the In-line type. After that, we estimated that the cooling performance was influenced the change in the environment such as the effect of the pulse-tube inclination and



changes in the temperature and flowing quantity of cooling water. The details of these experiment results are reported in this paper.

## 2. General design

Fig. 1 and Table 1 show a photograph of the prototype U type pulse tube cryocooler and its specifications, respectively. The cryocooler is an integral Stirling type pulse tube and the compressor that makes two pistons opposition is moved by the linear motor, with outer diameters of 330 mm and 670 mm in length. The compressor has a moving magnet type motor with high efficiency and the piston is guided by a flexure bearing. The piston position is monitored using a laser vibrometer. Pressure transducers are mounted near the compressor discharge head and a hot-end of the pulse-tube. The mass flow rate through the phase-shifter can be estimated by the pressure at the hot-end of the pulse-tube. These measurements are used to calculate both the pressure-volume P-V work of the compressor and an equivalent work (= work flow) of the pulse-tube. A PtCo sensor and a thermocouple were set up to measure the cold-head temperature and the temperature distribution of the regenerator and the pulse-tube wall, respectively. The inlet-outlet cooling water temperature of the after-cooler and the hot-end of the pulse-tube were measured with Pt100 sensors to calculate the heat capacity. We considered that the momentum equation of the inertance-tube was an equivalent LR circuit and the gas displacement in the inertance-tube was calculated by the measured pressure amplitude of the hot-end Ppt and the buffer-tank Pbf [3].

## 3. Results and Discussion

### 3.1. Prototype Cryocooler Performance

Fig. 2 shows the measured cooling performance of the prototype In-line and U type pulse tube cryocoolers. In regard to the arrangement of the cryocooler system, U type is smaller than an in-line type and more convenient for these applications. With the In-line type, the pulse-tube is located on the axis with the regenerator, but with the U type, the pulse-tube is parallel to the regenerator. The system was filled with helium gas up to 2.0 MPa and the vacuum chamber was evacuated to an order of  $<0.13$  Pa ( $10^{-3}$  torr). A radiation shield was rolled in to surround the expander. With 3.8

Table 1. Specifications of prototype U type STPC.

Maximum cooling power	: 190 W at 77 K
Maximum electric input power	: 3.8 kW (AC200 V)
Efficiency	: 14.5 % Carnot (COP 0.053)
Cooling	: Water cooling
Operating frequency	: 49 Hz
Initial gas pressure	: He 2.3 MPa
Dimension	: H750 mm × L700 mm × W350 mm
Weight	: <150 Kg
Expander	: Integral U type with inertance-tube

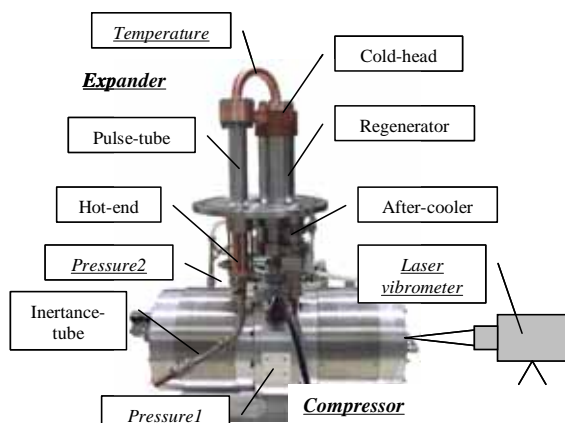


Fig. 1. Photograph of prototype U type STPC and measurement points of pressure, piston displacement and temperature.

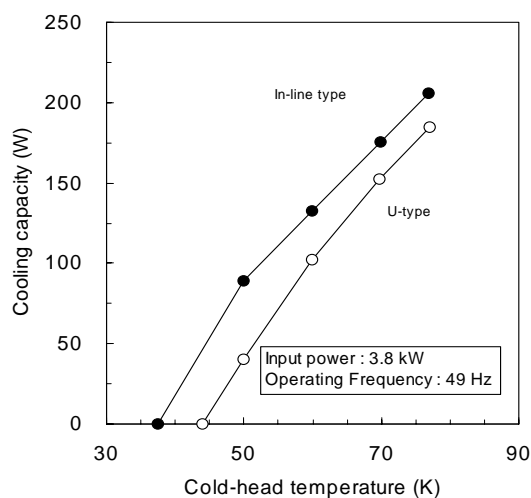


Fig. 2. Comparison of cooling capacity of the U type and the In-line type expander.

kW input power at the operating frequency of 49 Hz, the no-load temperature was 37 K, the cooling capacity was 210 W at 77 K and the compressor P-V work was about 2820 W. The compressor efficiency is 74 % at a motor efficiency 85 % at 77 K. The performance of the U type is 191 W at 77 K with the no-load temperature at 44 K. The performance decreased about 9.1 % compared to that of the In-line type, having a cooling capacity of 210 W at 77 K. It is suggested that a cold head's shape has a great effect on cooling performance. Because the volume of the cryocooler increases, the system was filled with helium gas up to 2.3 MPa. The pulse-tube work flow was calculated from the experimental results about 530 W at the cold-head temperature 77 K. These work flows go through the hot-end of the pulse-tube and are rejected as a heat in the phase controller. For improving efficiency of a pulse tube cryocooler, it's necessary to add a mechanism which can recover this work flow.

### 3.2. Influence of Pulse Tube Cryocooler Inclination

In 2010, G. W. Swift *et al.* reported the influence of a pulse-tube inclination by natural convection [4]. The performance of the pulse tube cryocooler depends on that inclination by influence of the natural convection in the pulse-tube. The operating conditions must be determined to minimize the effect of this inclination. In general, the convection loss can be reduced by high operating frequency and small pulse-tube size. We measured the effect of the U type pulse tube cryocooler inclination on the performance at a temperature higher than 65 K, as used by HTS. The influence of inclination was a decreasing rate within only 3 %.

### 3.3. Influence of Expander and Compressor Configuration

It may be advantageous to use a split configuration of the compressor and the expander where only the expander is installed in a system, because the weight of the cryocooler increases when the cooling capacity increases. The cooling capacity of the split expander was measured and compared to the integral type. The connecting tube used between the expander and compressor was a stainless tube in a straight line, with a 25.4 mm outer diameter and 1m length. The results show that almost the same performance is achieved between the split and integral configuration.

### 3.4. Evaluation Cryocooler Performance

It is necessary to remake the structure of the cold-head to set up the cryocooler in HTS system. Because the prototype cold-head doesn't have the place for connecting the large size equipment, the

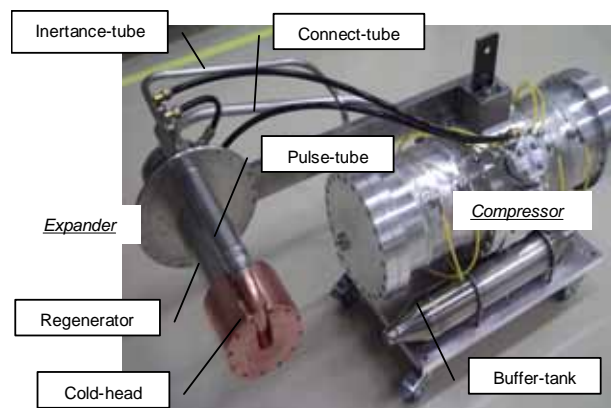


Fig 3. Photograph of an evaluation STPC for HTS system.

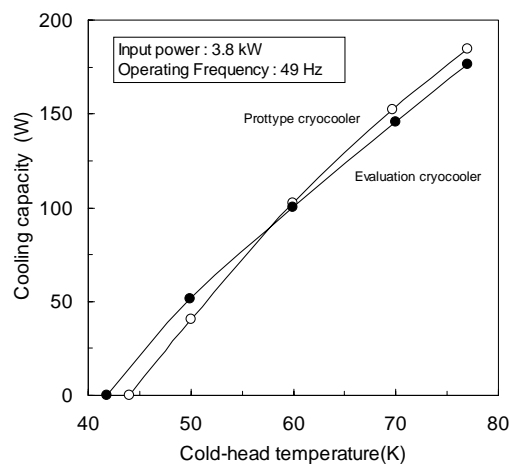


Fig 4. Comparison of cooling capacity of a prototype and an evaluation cryocooler.

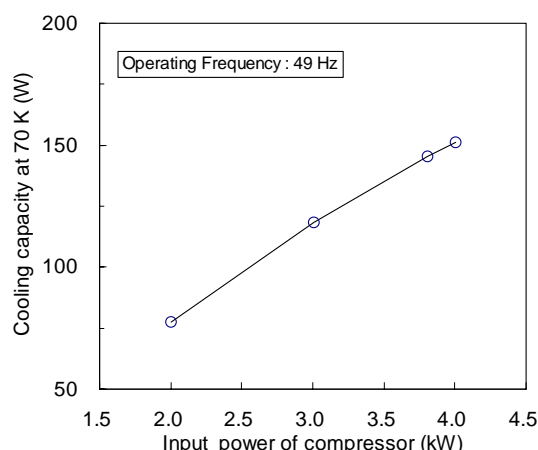


Fig 5. Measured cooling capacity at the cold-head temperature 70 K vs. the compressor input power for the evaluation SPTC.

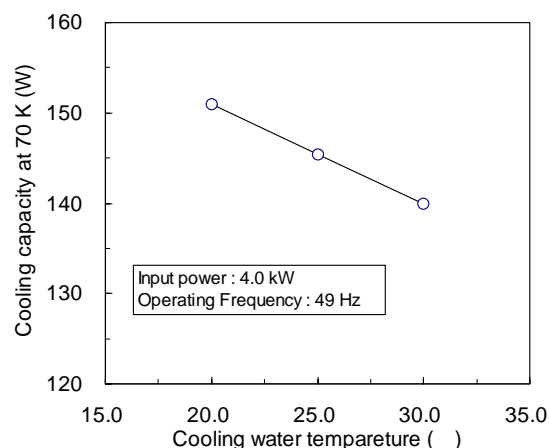


Fig 6. Measured cooling capacity at the cold-head temperature 70 K vs. the water cooling temperature for the evaluation SPTC.

low temperature part of the regenerator and the pulse-tube was connected in the tube as shown in Fig. 1. And an evaluation cryocooler re-designed an interface of the cold-head for HTS system and was examined. As for Fig. 3, 4, a photograph of the evaluation cryocooler and the comparison of the cooling performance examination results of the prototype and the evaluation cryocooler to estimate the HTS system are shown respectively. The performance of the evaluation cryocooler was 176 W at 77 K, with the no-load temperature at 42 K and decreased about 7.9 % compared to that of the prototype cryocooler. The heat conduction loss grows, because the distance of the place where the HTS device was set up from the low temperature heat exchanger in the end of the regenerator was so long and the cooling capacity decreased as a result. The cooling capacity that the HTS system needs has been over 150 W at 70 K and a necessary cooling capacity could be obtained 151 W at 70 K by the compressor input 4 kW as shown in Fig. 5. Moreover, the result of examining the influence on the cooling capacity by the difference of the inlet cooling water temperature is shown in Fig. 6. It is understood that the cooling capacity at 70 K decreases by 12 W when the inlet temperature of cooling water increases by about 10 °C.

#### 4. Conclusion

We developed a prototype SPTC with cooling capacity of 191 W at 77 K and a COP of 0.05. However, it was necessary to remake the structure of the cold-head to set up the cryocooler in HTS system and the evaluation cryocooler was designed and estimated. The performance of the evaluation cryocooler was 151 W at 70 K when the compressor input power was 4 kW at the operating frequency of 49 Hz.

#### References

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