Development of Orientation-Free High Power Stirling-Type Pulse Tube Cryocooler

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ABSTRACT

For the purpose of cooling high-temperature superconductor (HTS) devices, superconducting motors, SMES, and fault current limiters, a large cooling capacity Stirling-type Pulse tube cryocooler (SPTC) has been developed by Sumitomo Heavy Industries, Ltd (SHI). The design concepts of the cryocooler are high efficiency, compact size, light weight, and high reliability.

We have developed a cryocooler with a design target of producing a cooling capacity of 200 W at 77 K. As the experimental results show, the cooling performance of the in-line type expander achieved a cooling capacity of 210 W at 77 K, a minimum temperature of 37 K with a compressor input power 3.8 kW, an operating frequency of 48 Hz~60 Hz, and a compressor efficiency of 74%. Moreover, for miniaturization, a U-type expander was tested, and the performance is about 10% less than that of an in-line type expander. The cooling capacity degradation caused by inclination of the expander was within 3%.

The experimental results of the high power SPTC are reported in this paper.

INTRODUCTION

Recently technical innovation of HTS devices has brought about the necessity of high efficiency cryocoolers. Pulse tube cryocoolers, which have no moving parts at the cold section, are more attractive than other small cryocoolers because of their higher reliability, simpler construction, and lower vibration levels. Pulse tube cryocoolers cool by adiabatic expansion of a gas piston. The gas piston phase angle is controlled and optimized by a phase-shifter. In 1992, Chan, C.K. et al. developed a SPTC with a cooling capacity of 1W at 80K[1], similar to the power required for a Stirling cryocooler. Since then, many pulse tube cryocooler developments have been reported; however, they are mainly for military or spaceborne application. Recently, pulse tube cryocoolers with 100~1000W at 77K cooling capacity have been developed for HTS applications. In 2004, J. H. Zia et al. reported a commercial prototype SPTC with 200W cooling capacity as civilian equipment for HTS electronics applications.[2] We designed a prototype cryocooler to investigate the feasibility of fabricating a long-life and low-noise cryocooler with the objective of cooling HTS devices.

This paper describes the development of a prototype SPTC with a design target cooling capacity of 200W at 77K. We describe measured results for the cryocooler performance. A schematic drawing of the proposed U-type pulse tube cryocooler is shown in Figure 1 and its first target specifications are shown in Table 1.

Table 1. 1st Target Prototype Specifications.

Maximum cooling power	
	: 200W at 77K
Maximum electric input power	
	: 3.8kW (AC200V)
Efficiency	:14.5% Carnot (COP 0.053)
Life time	: >50,000hours
Cooling	: Water cooling
Operating frequency	
	: 45Hz～60Hz
Initial gas pressure	
	: He 2.0～3.0MPa
Dimension	
	:H800mm×L670mm×W350mm
Weight	: <150Kg
Expander	: Integral U-type with inertance-tube

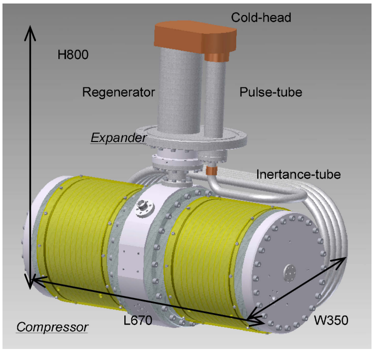

Figure 1. Schematic of 1st target prototype U-type pulse tube cryocooler.

GENERAL DESIGN

Figure 2 shows a photograph of the prototype in-line pulse tube cryocooler. The cryocooler is an integral Stirling-type pulse tube, and the compressor has opposed pistons driven by a linear motor, with outer diameters of 330 mm and 670 mm in length, respectively. The compressor has a moving magnet-type motor with high efficiency, and the piston is guided by a flexure bearing. The compressor is connected to the expander by connecting tubes of about 100 mm in length.

The piston position is monitored using a laser vibrometer. Pressure transducers are mounted near the compressor discharge head and the 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 the equivalent P-V work of the expander. To measure the cold-head temperature and the temperature distribution of the regenerator and the pulse tube wall, a PtCo sensor and a thermocouple are used, respectively. To calculate the cooling capacity, the inlet-outlet cooling water temperatures of the after-cooler and the hot end of the pulse tube are measured with Pt100 sensors.

RESULTS & DISCUSSION

Cryocooler Performance

Figure 3 shows the measured cooling performance of the prototype in-line pulse tube cryocooler. The system was filled with helium gas up to 2.0 MPa, and the vacuum chamber was evacu-

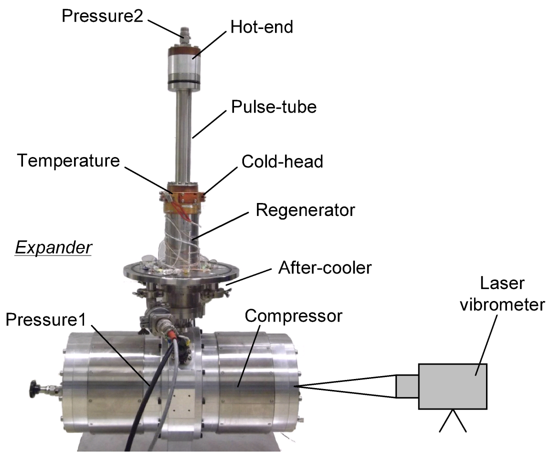

Figure 2. Photograph of prototype in-line Pulse tube cryocooler and measurement points of pressure, piston displacement and temperature.

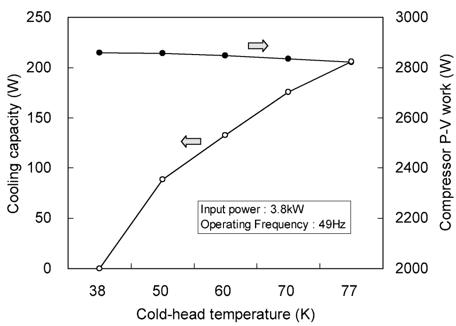

Figure 3. Measured cooling capacity and compressor P-V work vs. cold-head temperature

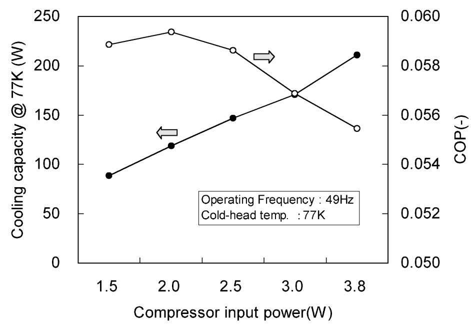

Figure 4. Measured cooling capacity and COP vs. compressor input power.

ated to an order of <0.13 Pa (10^{-3} torr). The diameter and length of the regenerator, the pulse tube, and the inertance-tube were optimized to get the best cooling capacity. A radiation shield has been rolled in to surround the expander. With 3.8 kW input power at the operating frequency of 48.5 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% (motor efficiency 85%), the specific power is 13.4 W/W at 77 K. The pressure ratio, Pmax/Pmin, is 1.29 in the compressor and 1.17 at the hot end of pulse tube. The final target of the compressor efficiency is over 80%. If the compressor efficiency goes up, performance of the system increases.

Figure 4 shows the efficiency and the cooling capacity at 77 K versus the compressor input power. The efficiency achieved was 16.0% Carnot at 3.8 kW input power and the highest efficiency was 17.5% Carnot at 2.0 kW input power.

In 2007, J. Imura. et al. reported the development of a Stirling type pulse tube cryocooler[3] and noted that a large temperature difference existed in the radial direction of the regenerator wall. However, we observed no problem at this time.

Difference in Expander-Type Performance

In regard to the arrangement of the cryocooler system, the U-type is more compact and is more convenient for this application. We considered whether the cooling performance is influenced by the expander type. With the in-line type, the pulse tube is located on the same axis as the regenerator, but with the U-type shown in Figure 5, the pulse tube is parallel to the regenerator.

Figure 6 shows that the performance of the U-type is 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, having a cooling capacity of 210 W at 77 K. It is suggested that a cold head's shape has a great effect on

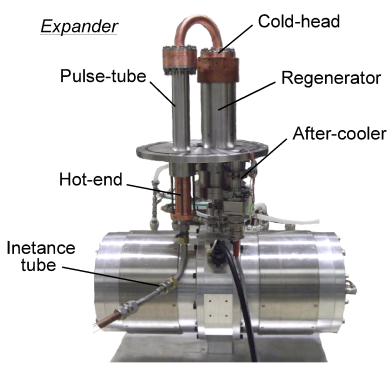

Figure 5. Photograph of prototype U-type Pulse tube cryocooler.

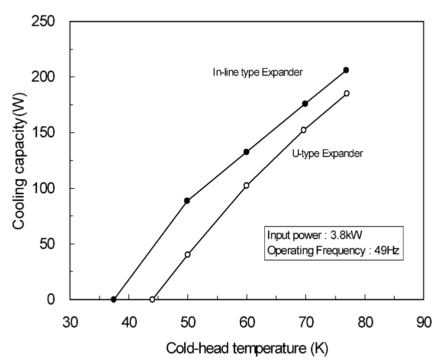

Figure 6. Comparison of cooling capacity of U-type and in-line type expander.

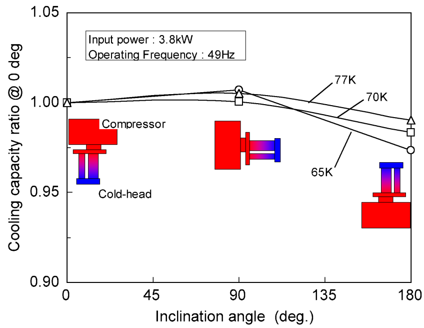

Figure 7. Influence of pulse tube inclination on relative cooling capacity.

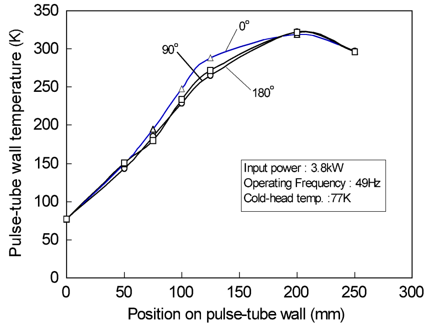

Figure 8. Temperature distribution along pulse tube wall for three pulse tube inclinations.

cooling performance. Because the volume of the cryocooler increases when going from in-line to U-tube, the system was filled with helium gas up to 2.3 MPa, and the operating frequency was changed to 49 Hz.

Influence of Pulse Tube Cryocooler Inclination

The performance of a pulse tube cryocooler may depend on a pulse tube's inclination by natural convection. A Pulse tube cryocooler used in these applications may require such inclination. The operating conditions must be determined to minimize the effect of this inclination. In general, high operating frequency and small pulse tube size reduces the convection loss.

We measured the effect of the pulse tube inclination on the performance at a temperature higher than 65 K, as used by HTS. The cooling capacity ratio at 77 K, 70 K and 65 K from 0 degrees to 180 degrees from the vertical direction is shown in Figure 7. The cooling capacity ratio is the cooling capacity at each angle divided by the pulse tube cold-head cooling capacity when oriented downward. The influence of inclination was relatively small, within 3% at any temperature. It is suggested by this graph that there are no strong influences of pulse tube inclination for temperatures over 65K, and there is only a little change in the temperature distribution of the pulse tube as shown in Figure 8.

In 2010, G.W.Swift. et al. reported on the influence of pulse tube inclination by natural convection;[4] they concluded that steady convection is suppressed when the pulse-convection number (Nptc) > 2 when the pulse tube aspect ratio D/L is small. Nptc is calculated by the following formula:

$$Nptc = \frac{\omega^2 a^2}{g(\alpha D \sin\theta - L\cos\theta)}\left(\frac{\Delta T}{T_{ave}}\right)^{\beta} \geq 2 \qquad [90 \leq \theta \leq 180] \tag{1}$$

In our cooler, the pulse tube aspect ratio D/L=0.16, the radian frequency ω = 307.9 (rad/sec), α=1.5, β=1, ΔT=243 K, the gas displacement a=0.15 (m), θ=180. This gives a value of Nptc = 30.4, which is much larger than Nptc=2. Moreover, P.Spoor evaluated Nptc using his company's cryocooler in 2011, and reported it was necessary for Nptc >30 to reduce the influence of convection.[5] As a result, our absence of convection with Nptc = 30.4 is very reasonable.

Influence of Expander and Compressor Configuration

Because the weight of the cryocooler increases as the cooling capacity increases, it may be advantageous to use a split configuration of the compressor and the expander where only the expander is installed in a system. 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. A photograph of

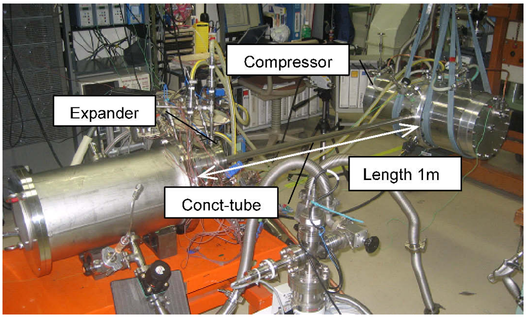

Figure 9. Photograph of experimental equipment for an investigating the split configuration of the compressor and the expander.

Table 2. Influence of the configuration of the compressor and the expander.

Expander type	Connecting tube size	Cooling Capacity @ 77K (W)
Integral	ID25×L100	192.9
Split	ID25×L1000	191.7

experiment equipment of the split configuration is shown in Figure 9, and the test results are shown in Table 2. The results show that nearly the same performance is achieved when comparing the split and integral configurations.

CONCLUSION

We developed a SPTC and the significant results of our research are:

(1) For 3.8 kW input power, the no-load temperature was 37 K and the cooling capacity was 210 W at 77 K with an in-line type expander, the efficiency was 16.0% Carnot. The highest efficiency was 17.5% Carnot at 2.0 kW input power.

(2) The compressor efficiency was 74% (motor efficiency 85%) and the indicated specific power was 13.4 W/W at 77 K.

(3) The performance degradation caused by inclination was about 3% for our SPTC.

(4) Cooling capacity of the U-type expander decreased about 9.1% compared to that of the in-line configuration.

(5) There was no significant reduction in cooling capacity for the split configuration of the compressor and the expander.

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