

# Development status of a high cooling capacity single stage pulse tube cryocooler

T Hirayama<sup>1</sup>, R Li<sup>2</sup>, M Y Xu<sup>1</sup> and S W Zhu<sup>3</sup>

<sup>1</sup>Technology Research Center, Sumitomo Heavy Industries, Ltd., 2-1-1 Yato-Cho, Nishitokyo-City, Tokyo 188-8585, Japan

<sup>2</sup>Precision Equipment Group, Sumitomo Heavy Industries, Ltd., 2-1-1 Yato-Cho, Nishitokyo-City, Tokyo 188-8585, Japan

<sup>3</sup>School of Mechanical Engineering, Tongji University, 4800 Cao'an Road, Shanghai 201804, P.R.China

E-mail: takashi.hirayama@shi-g.com

**Abstract.** High temperature superconducting (HTS) applications require high-capacity and high-reliability cooling solutions to keep HTS materials at temperatures of approximately 80 K. In order to meet such requirements, Sumitomo Heavy Industries, Ltd.(SHI) has been developing high cooling capacity GM-type active-buffer pulse tube cryocooler. An experimental unit was designed, built and tested. A cooling capacity of 390.5 W at 80 K, COP 0.042 was achieved with an input power of approximately 9 kW. The cold stage usually reaches a stable temperature of about 25 K within one hour starting at room temperature. Also, a simplified analysis was carried out to better understand the experimental unit. In the analysis, the regenerator, thermal conduction, heat exchanger and radiation losses were calculated. The net cooling capacity was about 80% of the PV work. The experimental results, the analysis method and results are reported in this paper.

## 1. Introduction

Since the pulse tube cryocooler was invented in 1964[1], it has attracted many researchers because of its simple structure[2-5]. Pulse tube cryocoolers have beneficial features such as low vibration, high reliability and low motor torque due to no moving parts in cryogenic region. SHI has been developing pulse tube cryocoolers since 1999. Development has focused on low vibration at the 4 K region[6-9].

Recently, the improvement in HTS materials lead to new developments of various applications such as HTS motor, power transmission cable and power generator, etc. Those applications require high-capacity and high-reliability cooling solutions to keep HTS materials at temperatures in the region of approximately 80 K. SHI has been developing a high cooling capacity single stage GM cryocooler to meet such requirements[10]. However, it is difficult to achieve a high cooling capacity of hundreds watt with GM cryocoolers. As cooling capacity increases, the size of the displacer increases. Thus, a large motor is required to drive the displacer. To solve this problem, pulse tube cryocoolers are considered because there are no displacer.

Since 2015, SHI has been developing a high cooling capacity pulse tube cryocooler. In this



paper, both the latest development status and the analysis results for a GM-type active-buffer pulse tube cryocooler are reported.

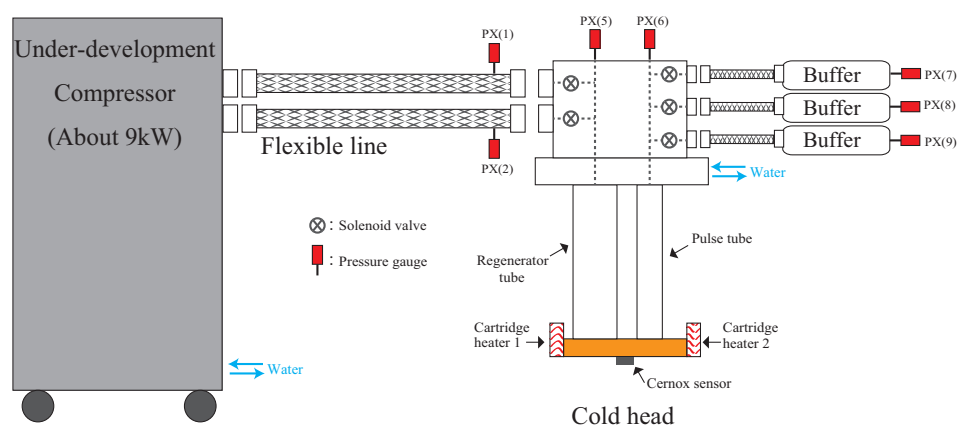
## 2. Experimental set-up and results

### 2.1. Experimental set-up

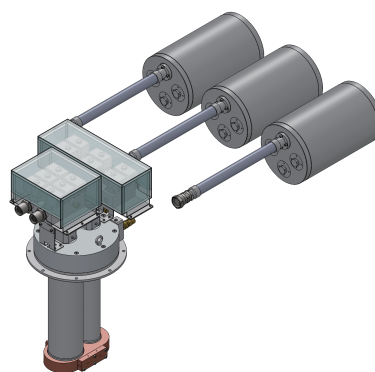
Figure 1 shows a schematic diagram of the experimental set-up. The heat load is generated by two cartridge heaters which are mounted on the cold stage. A cernox sensor (Lakeshore) is mounted on the cold stage to measure temperature, and pressure gauges are mounted on the high pressure line (PX(1)), low pressure line (PX(2)), room temperature end of the regenerator (PX(5)), room temperature end of the pulse tube (PX(6)), and the buffers (PX(7), PX(8), PX(9)). A compressor with an input power of approximately 9 kW is used to supply gas to the cold head. The compressor and the room temperature flange of the cold head are water-cooled. Solenoid valves (CKD) are used and the valves are controlled by a programmable logic controller (Mitsubishi Electric). Experimental conditions are as follows,

- The static filling pressure is 1.70 MPa.
- The compressor is operated at 50 Hz.
- The cold head is operated at 1.25 Hz.

Figure 2 shows a 3D diagram of the cold head.



**Figure 1.** Schematic diagram of the experimental set-up.

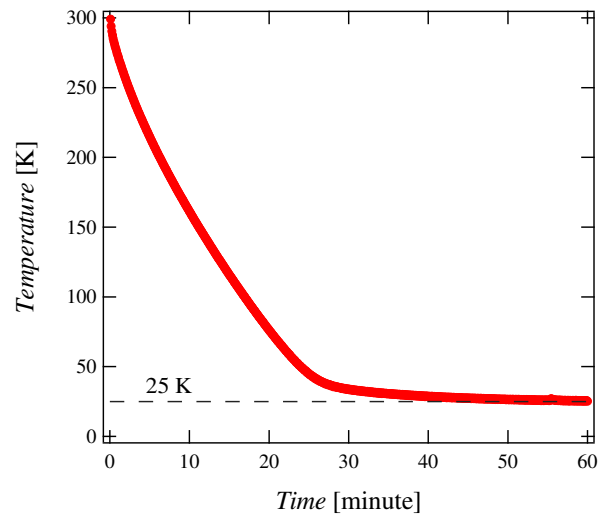


**Figure 2.** 3D diagram of the cold head.

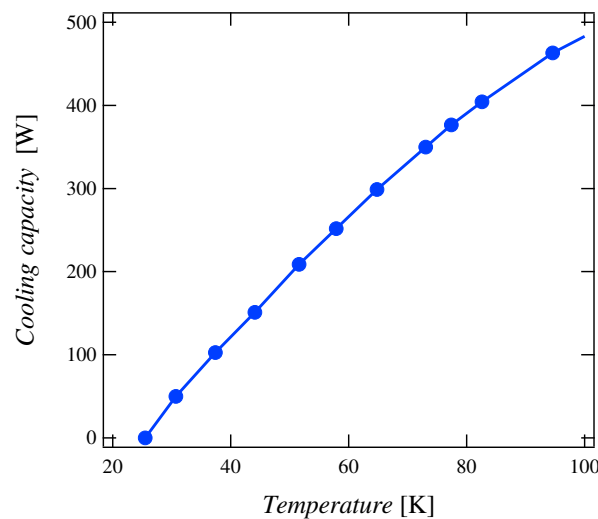
## 2.2. Experimental results

Figure 3 shows a typical cool-down process under no-load conditions. The cold stage usually reaches a stable temperature of approximately 25 K within one hour.

Figure 4 shows a typical cooling load-map. The no-load temperature was 24.5 K with an input power of 8.4 kW. A cooling capacity of 390.5 W at 80 K was achieved with an input power of 9.3 kW.



**Figure 3.** Typical cool-down process from room temperature.



**Figure 4.** Typical cooling load-map.

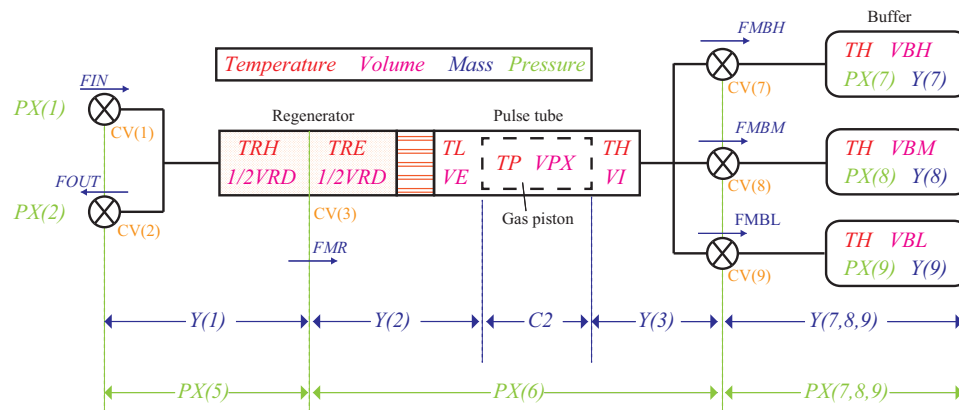
### 3. Analysis method and results

#### 3.1. Analysis method

Matsubara proposed a simplified analysis method for an orifice type pulse tube cryocooler[11]. This method is based on the conditions as follows,

- Regenerator is separated into two regions.
- Pressures at the regenerator cold end and in the pulse tube are the same.
- Consider helium gas as an ideal gas.
- Mass of the gas piston( $C2$ ) is constant.
- The initial  $VI$  is adjusted so that the upper end of the gas piston overlaps with the warm end of the pulse tube as the gas piston reaches its upper limit. Also, the initial  $VE$  is adjusted so that the lower end of the gas piston overlaps with the cold end of the pulse tube as the gas piston reaches its lower limit.

Figure 5 shows an analysis model of an active-buffer type pulse tube cryocooler.



**Figure 5.** Analysis model of an active-buffer type pulse tube cryocooler.

Equations which should be solved are as follows. These differential equations are solved by Runge-Kutta-Gill method.

Continuity equations are,

$$\left\{ \begin{array}{l} \frac{dY(1)}{dt} = FIN - FOUT - FMR \\ \frac{dY(2)}{dt} = FMR \\ \frac{dY(3)}{dt} = -FMBH - FMBM - FMBL \\ \frac{dY(7)}{dt} = FMBH \\ \frac{dY(8)}{dt} = FMBM \\ \frac{dY(9)}{dt} = FMBL \end{array} \right. \quad \begin{array}{l} (1a) \\ (1b) \\ (1c) \\ (1d) \\ (1e) \\ (1f) \end{array}$$

Mass flow equations are,

$$\left\{ \begin{array}{l} FIN = CV(1)\sqrt{PX(1)^2 - PX(5)^2} \\ FOUT = CV(2)\sqrt{PX(5)^2 - PX(2)^2} \\ FMR = CV(3)\{PX(5)^2 - PX(6)^2\} \\ FMBH = CV(7)\sqrt{PX(6)^2 - PX(7)^2} \\ FMBM = CV(8)\sqrt{PX(6)^2 - PX(8)^2} \\ FMBL = CV(9)\sqrt{PX(6)^2 - PX(9)^2} \end{array} \right. \begin{array}{l} (2a) \\ (2b) \\ (2c) \\ (2d) \\ (2e) \\ (2f) \end{array}$$

where  $CV(1)$  and  $CV(2)$  are the flow coefficient of the valves between the regenerator, and the high and low sides of the compressor, respectively.  $CV(3)$  is the flow coefficient of the regenerator.  $CV(7)$ ,  $CV(8)$  and  $CV(9)$  are the flow coefficient of the valves between the warm end of the pulse tube, and the high, medium and low pressure buffers, respectively.

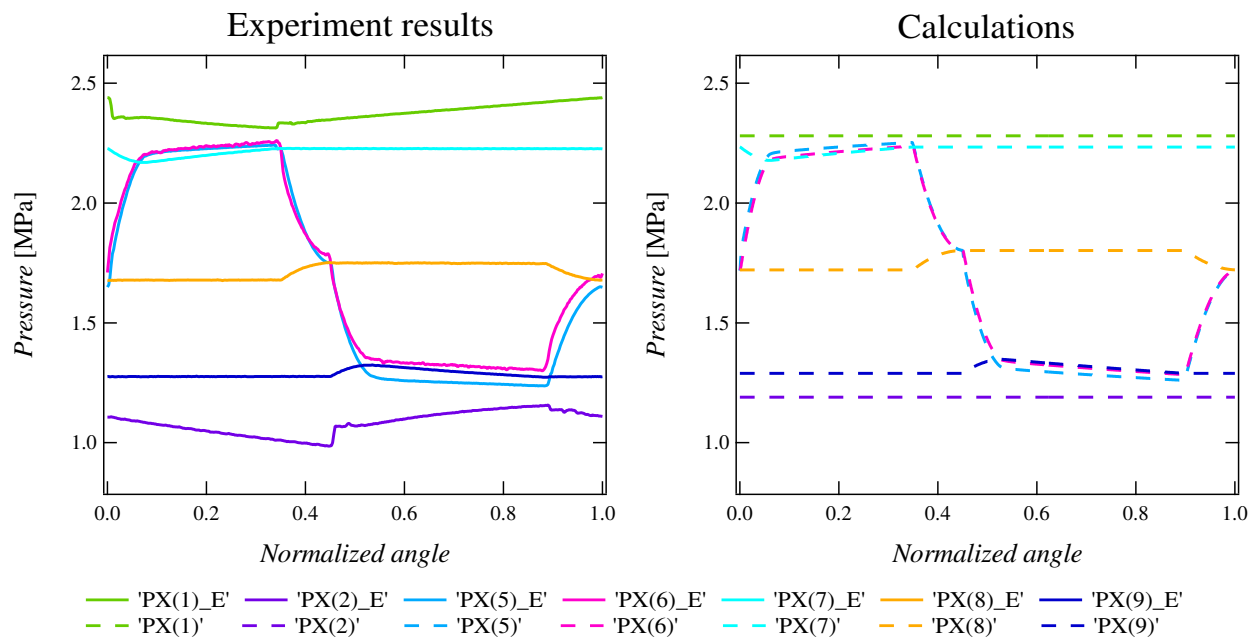
Ideal gas equations are,

$$\left\{ \begin{array}{l} PX(5) = \frac{Y(1) * R * TRH}{1/2VRD} \\ PX(6) = \frac{R\{Y(2) * TL + C2 * TP + Y(3) * TH\}}{VPT + \frac{TL}{TRE} * 1/2VRD} \\ PX(7) = \frac{Y(7) * R * TH}{VBH} \\ PX(8) = \frac{Y(8) * R * TH}{VBM} \\ PX(9) = \frac{Y(9) * R * TH}{VBL} \end{array} \right. \begin{array}{l} (3a) \\ (3b) \\ (3c) \\ (3d) \\ (3e) \end{array}$$

where  $R$  is the gas constant of helium.

### 3.2. Comparison with experiment

In order to verify the analysis method, the calculations are compared with the experimental results. Pressures in the system are shown in figure 6. Solid lines are experimental results and dotted lines are the calculations. The analysis results are very consistent with the experimental results.



**Figure 6.** Comparison of the calculations with the experimental results.

### 3.3. Analysis results of net cooling capacity and losses

Table 1 shows the analysis results of the cooling capacity and losses. The regenerator, thermal conduction, heat exchanger and radiation losses are calculated separately from the analysis calculations. It is estimated that the net cooling capacity is about 80% of the PV work. The regenerator loss is the largest. Therefore, the regenerator loss could be further reduced by optimization. It is difficult to reduce the thermal conduction and radiation losses as long as the physical size is not significantly changed. The calculated net cooling capacity is 443.7 W at 80 K. It is consistent with the experimental results (390.5 W at 80 K). The reasons for the differences are,

- in the analysis, the high and low pressures are assumed to be constant.
- in the analysis, the  $CV(3)$  is assumed to be constant.

**Table 1.** Analysis results.

Item	Results[W]
PV work	534.0
Regenerator loss	42.5
Thermal conduction loss	27.7
Heat exchanger loss	16.2
Radiation loss	3.9
Net cooling capacity	443.7

#### 4. Conclusions and future work

A high cooling capacity GM-type active-buffer pulse tube cryocooler was developed at SHI to meet HTS application required in 2015. A cooling capacity of 390.5 W at 80 K was achieved with an input power of 9.3 kW. Typical cool-down time is less than one hour. In that time, the temperature of the cold stage reaches approximately 25 K. Also, a simplified analysis was carried out to better understand of the experimental unit. It is estimated that the net cooling capacity is about 80% of the PV work. For future work, parameter optimization will be performed and the effect of the input power on the cooling capacity will be investigated.

#### References

- [1] Gifford W E, Longsworth R C 1964 *J. Eng. Ind.* **86**(3) 264-268
- [2] Mikulin E I, Tarasov A A, Shkrebyonock M P 1984 *Adv. Cryo. Eng.* **29** 629-637
- [3] Matsubara Y, Miyake A 1988 *Cryocoolers* **5** 127-135
- [4] Zhu S W, Wu P Y, Chen Z Q 1990 *cryogenics* **30** 514-520
- [5] Zhu S W, Kakimi S, Matsubara Y 1997 *cryogenics* **37** 461-471
- [6] Xu M Y, Gao J L, Seriz E, Longsworth R C, Saito M, Ikeya Y 2006 *AIP conf. Proc.* **823** 834-844
- [7] Nakano K, Xu M Y, Takayama H, Tsuchiya A, Saito M 2012 *AIP conf. Proc.* **1434** 532-539
- [8] Tsuchiya A, Lin X G, Takayama H, Saito M, Xu M Y 2014 *Cryocoolers* **18** 211-214
- [9] Xu M Y, Nakano K, Saito M, Takayama H, Tsuchiya A, Maruyama H 2012 *AIP conf. Proc.* **1434** 190-197
- [10] Bao Q, Xu M Y, Yamada K 2016 *cryocoolers* **19** 291-297
- [11] Matsubara Y 2007 *J. Cryo. Soc. Jpn.* **41** No 6