Development of High Efficiency 4K Two-Stage Pulse Tube Cryocooler

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ABSTRACT

Sumitomo Heavy Industries has been continuously improving the efficiency of our 4K pulse tube cryocooler in order to make it exchangeable with our 4K GM cryocooler. In order to improve the performance, three development model pulse tube cryocoolers have been built and tested. On the latest unit, the cooling capacity of the 4K pulse tube cryocooler has been improved to be equivalent to that of the 4K GM cryocooler. A typical cooling capacity of the latest pulse tube cryocooler is 40 W at 37.0 K on the first stage and 1.0 W at 3.86 K on the second stage when the compressor is operated at 50 Hz, and 40 W at 36.8 K on the first stage and 1.0 W at 3.82 K at 60 Hz. The input power is about 6.4 kW at 50 Hz and 7.7 kW at 60 Hz at steady state with 40 W heat load on the first stage and 1.0 W on the second stage. In addition, performance in a helium atmosphere has been measured and has been improved significantly by reducing the temperature difference between regenerator and pulse tube. The experimental results are described.

INTRODUCTION

Sumitomo Heavy Industries, Ltd. (SHI) has been continuously improving the efficiency of its 4K pulse tube cryocooler in order to make it exchangeable with its 4K GM cryocooler, with the added benefit of reduced vibration [1-2]. Our most recent version of our SHI 4K pulse tube has demonstrated significantly improved performance, equal to that of the 4K GM cryocooler.

In many applications, such as Magnetic Resonance Imaging (MRI), helium gas is directly recondensed with a cryocooler. In general, the performance becomes worse in a helium atmosphere than in vacuum because of heat conduction losses from the high temperature end to the low temperature end and heat convection loss between the cryocooler and sleeve [3-4]. For a 4K pulse tube cryocooler, performance degradation in a helium atmosphere becomes even worse because of extra heat convection between the regenerator tube and pulse tube.

In order to improve the performance, three pulse tube cryocoolers have been built and tested both in vacuum and in helium. In this paper, performance in vacuum and in a helium atmosphere are reported.

SYSTEM DESCRIPTION

Figure 1 shows a schematic of a SHI 1W 4K two-stage pulse tube cryocooler system. Photos of the cold head are shown in Figure 2. For comparison, the cold head of the previous model is also

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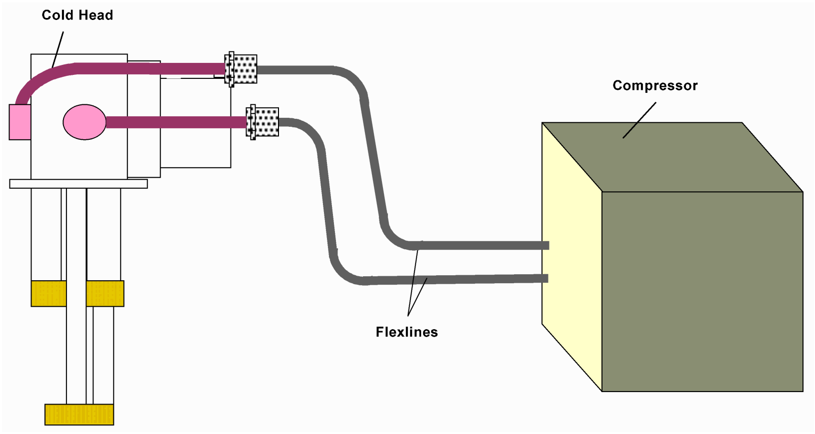
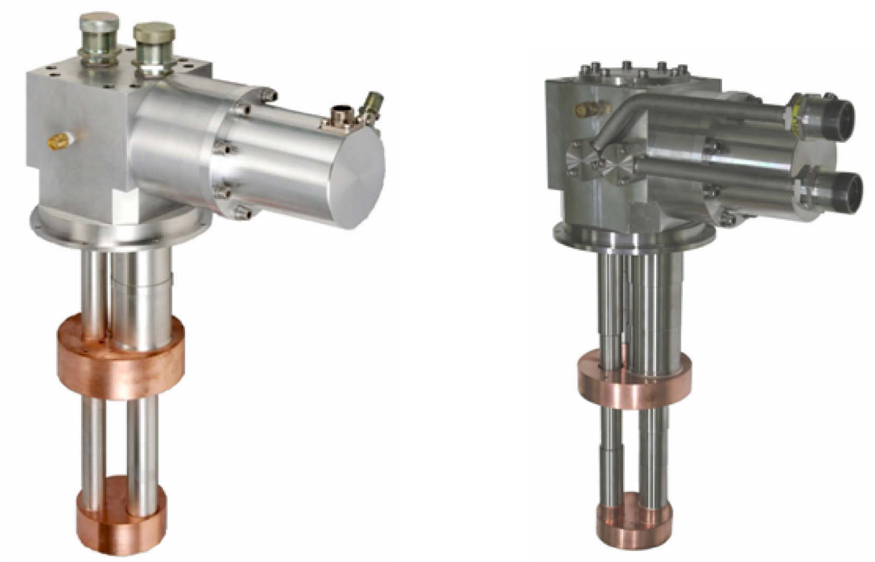


Figure 1. The system of a 1W 4K two-stage pulse tube cryocooler.



(a) (b)

Figure 2. Photos of cold head of SHI 1W 4K pulse tube cryocoolers: (a) previous model; (b) new model.

included. In order to make the cold head compact, the valve unit is integrated into the cold head. The design of the new model is similar to the previous model except for the direction of the self-sealed couplings. With the previous model, the self-sealed couplings are installed in a vertical direction. For the new model, the self-sealed couplings are installed horizontally in order to be exchangeable with our 4K GM cryocooler. A standard SHI F-series compressor, F-70, is used to generate the pressure oscillation. A new process for refining the oil and adsorber has been developed and the well refined oil and adsorber are used in all SHI F-series compressors. As a result, an adsorber exchange interval of 30,000 hrs has been achieved with the SHI F-series compressor.

In order to reduce pressure drop through the self-sealed couplings and flexlines, the diameter of the flexlines was increased from 19.05 mm (3/4") to 24.5 mm (1"). The size of the self-sealed couplings on the cold head were changed from 12.7 mm (1/2") to 19.05 mm (3/4").

A synchronous three-phase motor is used to drive the rotary valve unit, including a valve disc and a valve seat. In the 4K pulse tube cryocooler, the only moving part is the rotary valve. Wear dust generated from the valve is one of the major factors that affects performance. SHI has been making efforts to reduce the wear dust from the rotary valve.

A new low wear valve material has been developed and the wear rate has been reduced to about 1/3 of that compared to the valve material used in the previous models. Meanwhile, the area of the valve contact face has been reduced. The total amount of valve wear has been reduced to about 1/5.

In order to improve the performance, three units have been built; they are called: PT A, PT B, and PT C. PT A is a unit used to confirm the basic concept of the cold head with horizontal self-sealed couplings. PT B is a unit used to confirm the concept for improving the performance in a helium atmosphere. PT C is a unit used to confirm the effect of improved regenerators, flow smoothers, and heat exchangers.

PERFORMANCE IN HELIUM ATMOSPHERE

In general, performance becomes worse in a helium atmosphere than in vacuum [3-4]. Performance degradation in a helium atmosphere for a 4K GM cryocooler is caused by heat conduction between the top flange and the first stage, heat conduction between the first stage and the second stage, and heat convection between the sleeve and the cylinder of the cryocooler. Generally, heat convection loss is much larger than the heat conduction loss.

In order to understand how a 4K pulse tube works in a helium atmosphere, a cryostat was built. A schematic of the cryostat is shown in Figure 3. A sleeve is installed between the vacuum chamber and the cryocooler. The wall thickness of the sleeve is about 2 mm. The heat conduction loss from the top flange to the first stage is about 15 W. The sleeve can be evacuated or filled with helium. A

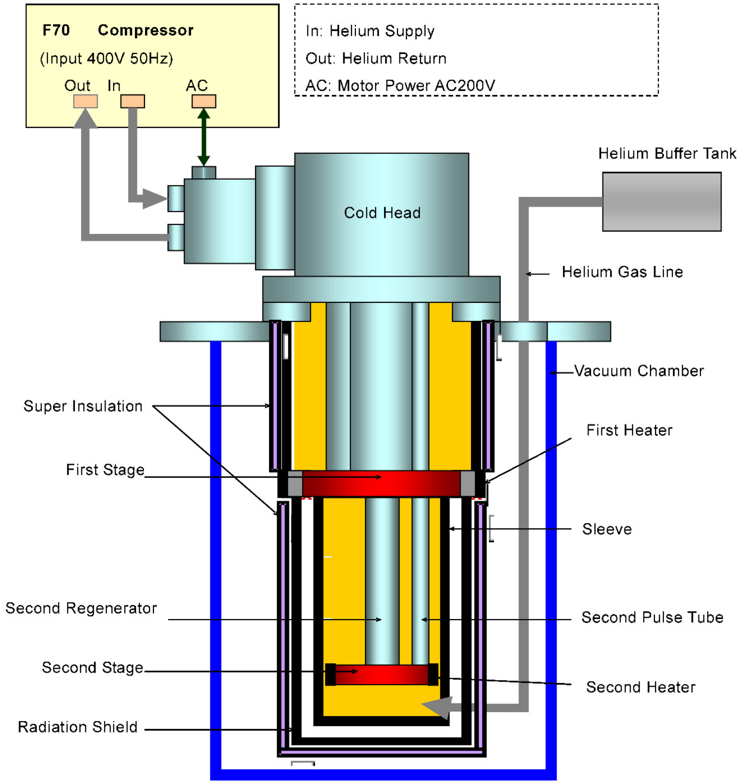


Figure 3. Cryostat for test in helium atmosphere.

Table 1. Performance In Sleeve (Vacuum or Helium).

		Temperature in Vacuum (K)	Temperature in Helium (K)
4K GM	First Stage @40W	42.7	44.7
	Second Stage @1.0W	3.68	3.91
4K PT (PT A)	First Stage @30W	42.7	45.8
	Second Stage @1.0W	3.97	4.35
4K PT (PT B)	First Stage @30W	46.7	51.3
	Second Stage @1.0W	4.02	4.26
4K PT (PT C)	First Stage @30W	40.8	46.8
	Second Stage @1.0W	3.78	3.96

5 liter buffer is connected to the sleeve. When the cryocooler is tested in a helium atmosphere, the static pressure in the sleeve is filled to 100 kPa at room temperature. Pressure in the sleeve is not controlled. Therefore, after cooldown, the pressure is almost equal to the saturation pressure at the temperature of the second stage.

A radiation shield is installed to cover the lower part of the sleeve to reduce radiation loss to the second stage. In order to reduce the radiation loss further, about 10 layers of super-insulation are used to cover the upper part of the sleeve, the radiation shield, regenerators, and pulse tubes.

Performance data are presented in Table 1 for the 4K GM and the three pulse tube cryocoolers for operation in vacuum and in a helium atmosphere. Unless it is stated, the compressor is operated at 50 Hz. The 4K GM is a standard SHI 1W 4K GM cryocooler. PT A is the pulse tube cryocooler used to confirm the basic concept of coldhead with horizontal self-sealed couplings, PT B is the unit used to confirm the concept for improving performance in a helium atmosphere, and PT C is the unit to confirm the effect of improved regenerators, flow smoothers, and heat exchangers.

For a 4K GM, the cooling capacity is 40 W at 42.7 K at the first stage and 1.0W at 3.68 K at the second stage when the sleeve is evacuated. The performance in vacuum is worse compared to that in a normal vacuum chamber without a sleeve. The extra heat conduction loss through the sleeve to the first stage is about 15 W. When the sleeve is filled with helium, the cooling capacity is 40 W at 44.7 K at the first stage and 1.0 W at 3.91 K at the second stage. The temperature increases 0.23 K when the sleeve is filled with helium.

Compared to the 4K GM, the performance degradation of PT A in helium is large because of the extra heat convection between the regenerator tube and pulse tube. The cooling capacity is 30 W at 42.7 K at the first stage and 1.0 W at 3.97 K at the second stage when the sleeve is evacuated. When the sleeve is filled with helium, the cooling capacity is 30 W at 45.8 K at the first stage and 1.0 W at 4.35 K at the second stage. When the sleeve is filled with helium, the temperature increases 0.38 K, which is worse than that of the 4K GM.

In order to improve the 4K pulse tube cryocooler performance in helium, the temperature difference between the regenerator and the pulse tube can be reduced by using a techniques such as installing a spacer in the cold end of regenerator [3]. PT B was built to improve the performance in a helium atmosphere. As shown in Table 1, the cooling capacity of PT B is 30 W at 46.7 K at the first stage and 1.0 W at 4.02 K at the second stage when the sleeve is evacuated. When the sleeve is filled with helium, the cooling capacity is 30 W at 51.3 K at the first stage and 1.0 W at 4.26 K at the second stage. The temperature increases 0.24 K when the sleeve is filled with helium. The performance degradation of PT B in helium has been improved and has become similar to that of the 4K GM cryocooler.

In order to understand the mechanism of performance degradation with the helium atmosphere, the temperature profile on the second stage regenerator and second stage pulse tube of PT A was measured. The temperature profile versus cylinder height is shown in Figs. 4a and 4b. Figure 4a shows the temperature profile in vacuum, while Fig. 4b shows the temperature with the helium atmosphere. The cylinder height is the distance from the top surface of the second stage heat station. On PT A, the temperature on the second regenerator is higher than the temperature on the

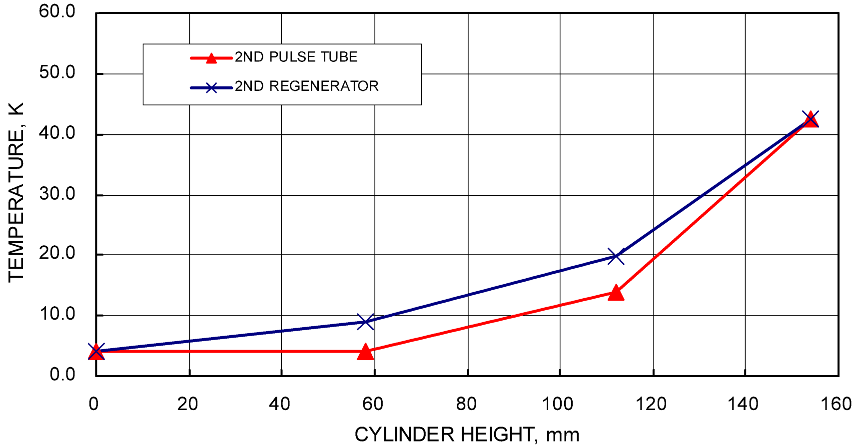


Figure 4a. Temperature profile for PT A in vacuum.

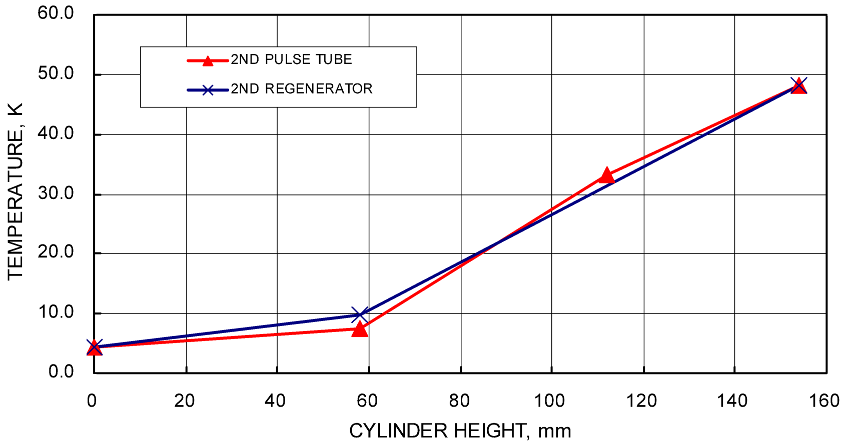


Figure 4b. Temperature profile for PT A in helium.

second pulse tube. When the tubes are surrounded by helium gas, the temperature difference becomes smaller. The reason is that heat is transferred from the regenerator to the pulse tube by natural convection. Therefore, the temperature profile on the pulse tube shifts because of extra heat convection that occurs between the regenerator tube and the pulse tube. Since orifices at the warm end of pulse tube are optimized based on the temperature profile in vacuum, orifice openings are not optimum for helium operation because of the temperature profile change. Especially, DC flow from the warm end to the cold end increases when the temperature profile gets higher. Consequently, performance on the second stage gets worse because of this kind of DC flow.

A simple way to reduce the temperature difference is to install a spacer into the cold end of the second stage regenerator, or connect the regenerator and the pulse tube with some heat bridges [3]. These methods were tested with PT B. The improved temperature profile is shown in Figs 5a and 5b. Figure 5a shows the temperature profile in vacuum and Fig. 5b shows the temperature with the helium atmosphere. On PT B, the temperature of the second regenerator is only a little higher than the temperature of the second pulse tube. When the tubes are surrounded by helium gas, there is almost no temperature difference between the second regenerator tube and the pulse tube. Therefore, as shown in Table 1, the performance degradation in helium atmosphere is reduced to a great degree.

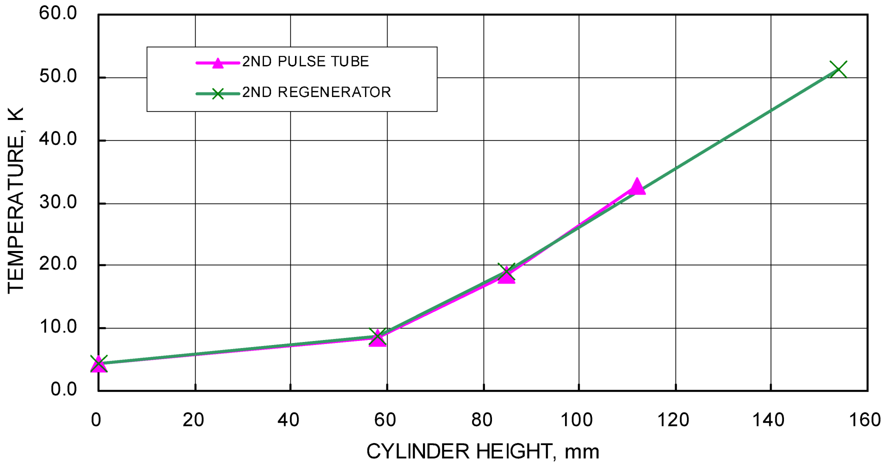


Figure 5a. Temperature profile for PT B in vacuum.

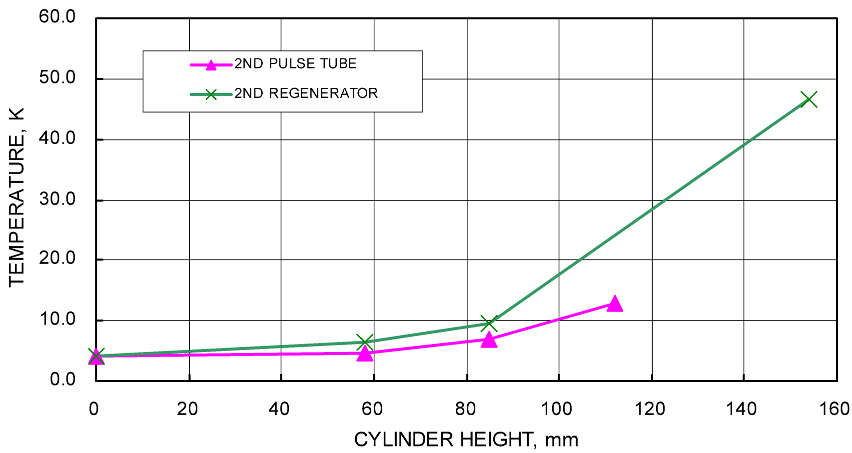


Figure 5b. Temperature profile for PT B in helium.

PERFORMANCE IMPROVEMENT

In order to improve the performance further, the regenerator, flow smoother, and the heat exchanger were improved. PT C was built for this purpose. A typical loadmap of cooling capacity of PT C at 50 Hz and 60 Hz is shown in Figure 6. The following cooling capacity was measured in a normal vacuum chamber without sleeve. The static charge pressure was 1.65 MPa. The lowest temperature is 23.3 K at the first stage and 2.36 K at the second stage at 50 Hz and 23.8 K and 2.43 K at 60 Hz. With 40 W and 1.0 W heat load, the first stage temperature is 37.0 K and the second stage temperature is 3.86 K at 50 Hz and 36.8 K and 3.82 K at 60 Hz. The input power is 6.4 kW at 50 Hz and 7.7 kW at 60 Hz. With 60 W and 1.0W heat load, the temperature is 50.4 K and 3.91 K at 50 Hz and 48.3 K and 3.94 K at 60 Hz.

CONCLUSION

The performance of the SHI 4K pulse tube cryocooler has been improved significantly to be equivalent to that of a 4K GM cryocooler. A typical cooling capacity is 40 W at 37.0 K on the first stage and 1.0 W at 3.86 K on the second stage when the compressor is operated at 50 Hz and 40 W at 36.8 K and 1.0 W at 3.82 K at 60 Hz. The input power is about 6.4 kW at 50 Hz and 7.7 kW at

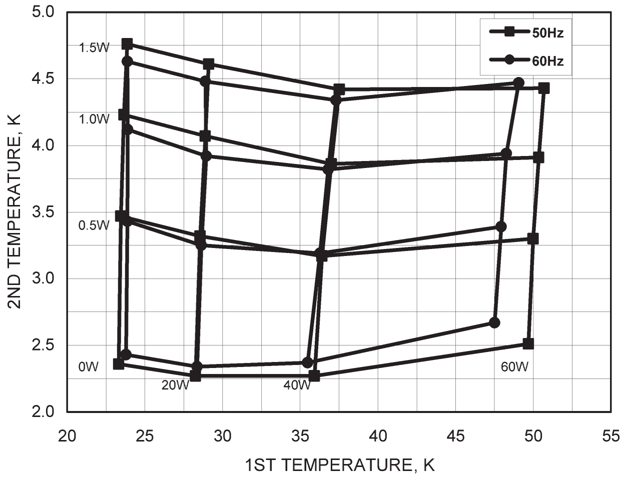


Figure 6 Typical loadmap of PT C.

60 Hz at normal steady state with 40 W heat load on the first stage and 1.0 W on the second stage.

The mechanism of performance degradation in helium atmosphere has been investigated by measuring the temperature profile on the regenerator and the pulse tube.

The performance in a helium atmosphere for a 4K pulse tube cryocooler has been improved to be similar to a 4K GM cryocooler by reducing the temperature difference between the regenerator and the pulse tube.

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