Development of a 2W 4 K Pulse Tube Refrigerator with Remote Valve

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ABSTRACT

A two-stage pulse tube refrigerator having a rated capacity of 60 W at 50 K and 2 W at 4.2 K has been developed by Sumitomo (SHI) Cryogenics of America, Inc. for applications such as large cryogen-free dilution refrigerators and superconducting magnets. This pulse tube refrigerator has a low-vibration design using a remote valve. The development of this pulse tube refrigerator and its performance characterization, including improvements in system efficiency, is described in this paper. A typical system provides 60 W at 48.0 K and 2.0 W at 4.05 K and a no-load temperature of 2.54 K with 50 Hz compressor operation. For 60 Hz operation, 60 W at 46.7 K and 2.0 W at 4.02 K as well as a no-load temperature of 2.29 K, are obtained with the same configuration. In characterization tests, this new pulse tube refrigerator shows a fast cooldown, good precooling performance, and low vibration that would meet requirements from various applications.

INTRODUCTION

The first pulse tube refrigerator was developed in 1963 by Gifford and Longsworth [1], and this technology has evolved significantly from its original design. Today, 4-Kelvin pulse tube refrigerators that possess low vibration and high reliability are commercialized and widely used in applications such as superconducting magnets, cryogenic detectors for cosmological observation, helium liquefiers, adsorption coolers, sub-Kelvin adiabatic demagnetization refrigerators, and dilution refrigerators.

SHI's RP-182B2S pulse tube refrigerator provides a cooling capacity of 1.5 W at 4.2 K with a remote valve [2]. The SHI team is continuously developing new pulse tube refrigerators with low vibration, higher capacity and efficiency to meet the challenge of future growth in emerging technologies. For instance, to scale up the quantum computer and dilution refrigerator, a larger cooling capacity is requested. For applications where multiple pulse tube refrigerators are used, the number of refrigerators can be reduced if a single refrigerator provides more. Moreover, reducing the cooldown and turnover time is desired to maximize the throughput of dilution refrigerators and accelerate the research projects. Other applications such as superconducting magnets and helium liquefiers also request higher cooling capacities. To meet these demands, SHI developed a larger remote-valve pulse tube refrigerator, RP-222B3S, with a cooling capacity of 2.0 W at 4.2 K. This paper presents the development of the new refrigerator and its performance characterizations including capacity maps, cooldown time, precooling performance and vibration.

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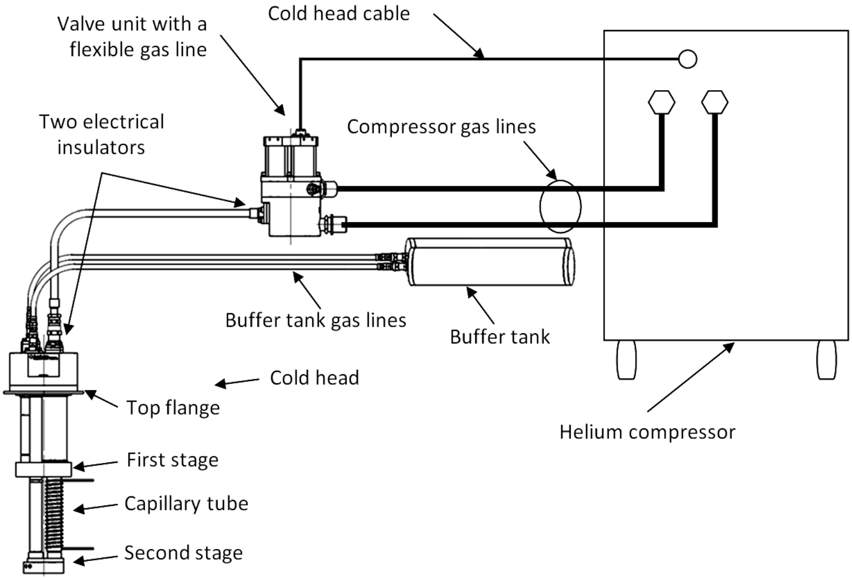

Figure 1. RP-222B3S pulse tube refrigerator system.

SYSTEM DESIGN

Due to the lower vibration requirement from the above-mentioned applications, our development focused on the remote valve configuration first. Regarding the phase-shifting mechanism, similar to the RP-062 model, the double-inlet phase shifter was selected for the new RP-222B3S pulse tube refrigerator. This new refrigerator also features some cylinder designs from the RP-182 model.

Referring to Figure 1, the new RP-222B3S pulse tube refrigerator consists of a two-stage cold head, a valve unit, two buffer tanks and two small gas lines. The valve unit has an attached flexible gas line connecting to the cold head, which periodically supplies the high- and low-pressure helium flows. In addition, two electrical isolators are installed to isolate electrical noise generated by the compressor and valve unit motor: one between the valve unit body and the flexible gas line and the other one between the cold head body and the flexible gas line. The two electrical isolators provide end-users with more flexibility of electrical grounding or isolation. An F-100 compressor is used to drive the RP-222B3S pulse tube refrigerator, and it has a power input from 11.5 to 14.5 kW depending on the line frequency and pressure conditions.

PERFORMANCE AND DISCUSSION

Table 1 summarizes the typical performance of the RP-222B3S pulse tube refrigerator at line frequencies of both 50 and 60 Hz. The performance results are obtained from the pulse tube refrigerator with the same configuration.

At the line frequency of 50 Hz, the first and second stage temperatures are 48.0 and 4.05 K, respectively, with loads of 60 W and 2.0 W, and the no-load second stage temperature is 2.54 K. The performance becomes slightly better with 60 Hz compressor operation. The power consumption at 60 Hz

Table 1. Typical performance of a RP-222B3S pulse tube refrigerator with 60 W and 2.0 W heat loads.

Line frequency	First stage temperature	Second stage temperature	Approximate power consumption with loads	Second stage temperature with no load
50 Hz	48.0 K	4.05 K	11.8 kW	2.54 K
60 Hz	46.7 K	4.02 K	14.5 kW	2.29 K

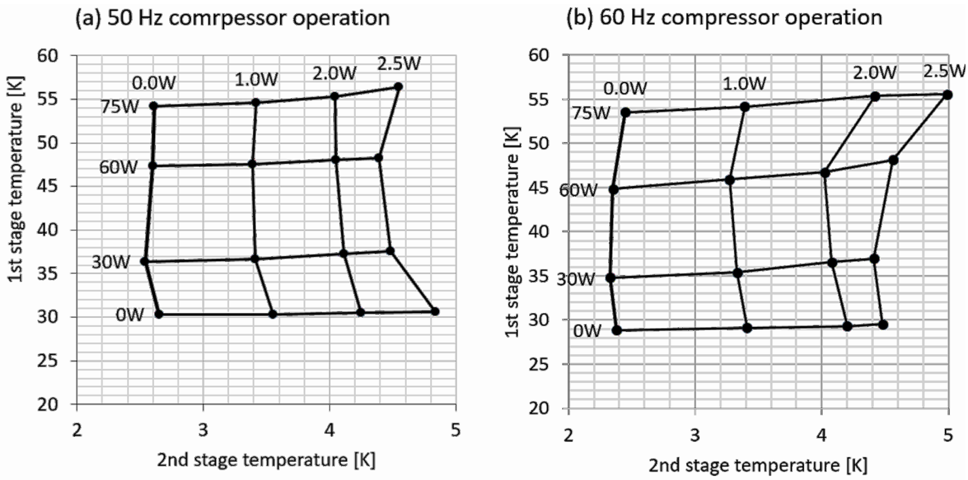

Figure 2. Capacity map of the RP-222 pulse tube refrigerator.

is increased due to the speed change of the compressor. While the cooling performance at 60 Hz does not increase proportionally with the increased power consumption. This is because the same pulse tube refrigerator is tested for both line frequencies, and the refrigerator is not optimally tuned for 60 Hz operation. The overall efficiency of the RP-222B3S pulse tube refrigerator is improved by more than by 20% compared to the RP-182B2S model.

Heat loads of 0-75 W and 0-2.5 W are applied on each stage, respectively, to investigate the performance of this new refrigerator under these loading conditions. Figure 2 (a) and (b) show the cooling capacity map at both 50 and 60 Hz line frequencies.

The operating frequency of a pulse tube refrigerator is an important factor for matching a compressor and maximizing its efficiency. The performance of the first and second stages with 60 W and 2.0 W loads has been tested at several operating frequencies, and the data is presented in Figure 3 (a) and (b).

Referring to Figure 3 (a), when the compressor runs at 50 Hz, the optimal operating frequency for the first stage performance is 1.1 Hz, which results in the lowest first stage temperature of 45.9 K. While the second stage temperature drops to 3.98 K monotonically if the operating frequency is reduced to 0.9 Hz. Considering the balance between both stages, the optimal operating frequency is 1.0-1.1 Hz.

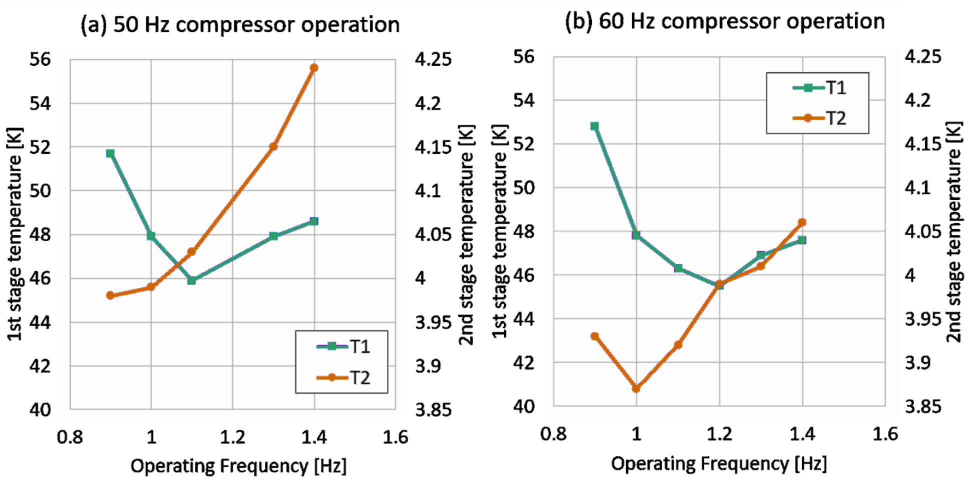

Figure 3. Optimization of the operating frequency of the RP-222 pulse tube refrigerator.

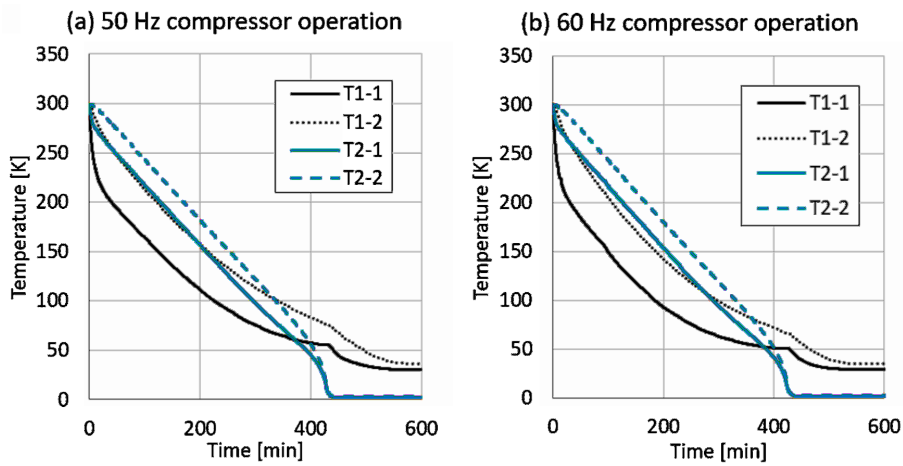

Figure 4. Cool-down test of the RP-222 pulse tube refrigerator with large thermal loads

For 60 Hz compressor operation, as shown in Figure 3 (b), the optimal operating frequency for the second stage is 1.0 Hz, where this refrigerator produces the best performance of 3.87 K with 2.0 W, which is equivalent to about 2.3 W at 4.2 K. The optimal motor frequency for the first stage performance is about 1.2 Hz. Therefore, in this case, the overall optimal frequency is 1.0-1.2 Hz. To balance the performance between 50 and 60 Hz compressor operation, an operating frequency of 1.0 and 1.2 Hz is used, respectively.

For applications like superconducting magnets and dilution refrigerators, the radiation shields and cold plates are usually much heavier than the heat stations of a pulse tube refrigerator. To investigate the cooldown time under these conditions, about 15 kg aluminum alloy (equivalent mass) and 30 kg copper are attached to the first and second stage heat stations, respectively, and cooldown tests are performed. Bolt mounting with thermal paste is used to improve the thermal contact between the loads and heat stations. Figure 4 (a) and (b) present the cooldown time of the RP-222B3S pulse tube refrigerator with large thermal mass loads attached. The temperatures on the first stage heat station (T1-1), first stage load (T1-2), second stage heat station (T2-1) and second stage load (T2-2) are monitored. With 50 and 60 Hz compressor operation, the cooldown time to 4.2 K is 7.26 and 7.20 hours, respectively. On average, this new pulse tube refrigerator cools down 9% faster than the existing RP-182B2S model. The temperature lag between the heat station and load is large at the beginning of the cooldown, and becomes significantly smaller when the whole system reaches a lower temperature. This indicates that the cooldown time could be further shortened if the thermal resistance between the load and the heat station is reduced.

The precooling performance of a 4 K pulse tube refrigerator has been studied by Zhu, et al. [3], and their work demonstrated that excessive cooling capacity could be extracted from the regenerator tube. This method is practically used in helium liquefiers and dilution refrigerators. The capillary tube shown in Figure 1 sometimes is brazed onto the second stage regenerator tube for precooling the feeding gas from an end user's application. To investigate the precooling performance, the heat load is applied on the first or second stage regenerator tubes and the impacts on the cooling capacity are summarized in Figure 5 (a) and (b). During the test, both stages are loaded with 60 W and 2.0 W, respectively, while the additional load is applied on either regenerator tube simultaneously.

As shown in Figure 5 (a), the first stage temperature rises from 48.0 K to 56.0 K when a load of 0 to 20 W is applied to the first stage regenerator tube. Meanwhile, the second stage temperature rises from 4.08 K to 4.60 K. If a load of 10 W is extracted from the first stage regenerator, the second stage temperature only rises from 4.08 K to 4.21 K, which results in a relatively small impact.

The second test applies a 0-3.0 W heat load on the second stage regenerator tube. Figure 5 (b) shows that the second stage temperature rises from 4.05 K to 4.70 K and the first stage temperature increases by 1.9 K only. With a load of 1.0 W, the second stage temperature rises from 4.05 K to 4.16 K, with an increment of 0.11 K only. Extracting cooling capacity from regenerator tubes results in degradation

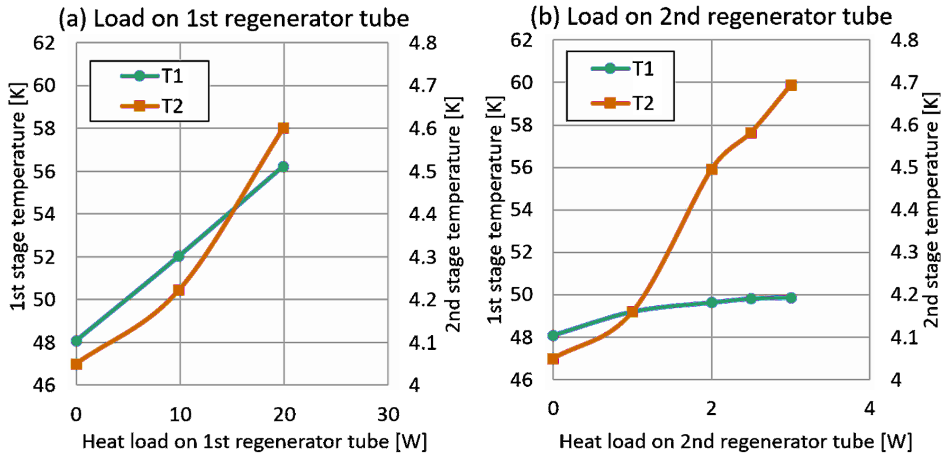

Figure 5. Pre-cooling performance using the regenerator tube.

Table 2. Displacement amplitude of an RP-222 pulse tube refrigerator. (The actual value varies depending on the applications.)

	1st stage 50 Hz	2nd stage 50 Hz	1st stage 60 Hz	2nd stage 60 Hz
X-axis	0.8 μm	5.5 μm	0.7 μm	5.8 μm
Y-axis	2.4 μm	8.6 μm	3.3 μm	9.4 μm
Z-axis	9.1 μm	13.2 μm	8.7 μm	14.3 μm

of the cooling performance, but in liquefaction and dilution refrigerator applications, the precooling is much more efficient than introducing the load to heat stations directly due to the temperature span for heat transfer.

The sound measurement is completed by setting up a microphone decibel level meter about 1 m away from the pulse tube refrigerator in operation. The maximum noise level is about 61dBA measured from different spots.

The displacement and acceleration of the RP-222B3S pulse tube refrigerator are also measured to demonstrate the vibration characteristics. The pulse tube refrigerator is installed on an anti-vibration table and operated without the vacuum shroud. A contactless laser displacement sensor is used to measure the displacement amplitude. An accelerometer is installed on each stage of the cylinder to measure the acceleration, and Fast Fourier Transform (FFT) analysis is implemented to demonstrate spectral information of acceleration amplitude.

Table 2 presents the test results of the displacement amplitude at line frequencies of both 50 and 60 Hz. In general, the second stage heat station at Z-axis has the largest displacement amplitude compared with the first stage heat station or other axes. The displacement amplitude on both stages is less than 10 μm at X- and Y-axes, while at Z-axis it is less than 15μm.

Figure 6 (a) – (c) show the Z-axis acceleration amplitude up to 1,000 Hz on each stage of the cylinder: top flange, first- and second-stage heat stations. On both the top flange and first stage heat station, the acceleration amplitude of the RP-222 pulse tube refrigerator is smaller than the RP-182 model. For the second stage heat station, the acceleration is at the same scale as the RP-182. Note that the actual displacement and acceleration amplitudes vary depending on the applications and cryogenic dewar configurations.

CONCLUSIONS

Sumitomo (SHI) Cryogenics of America, Inc. developed a high-capacity two-stage pulse tube refrigerator, RP-222B3S, with a rated capacity of 2.0 W at 4.2 K and 60 W at 50 K, as well as a no-load

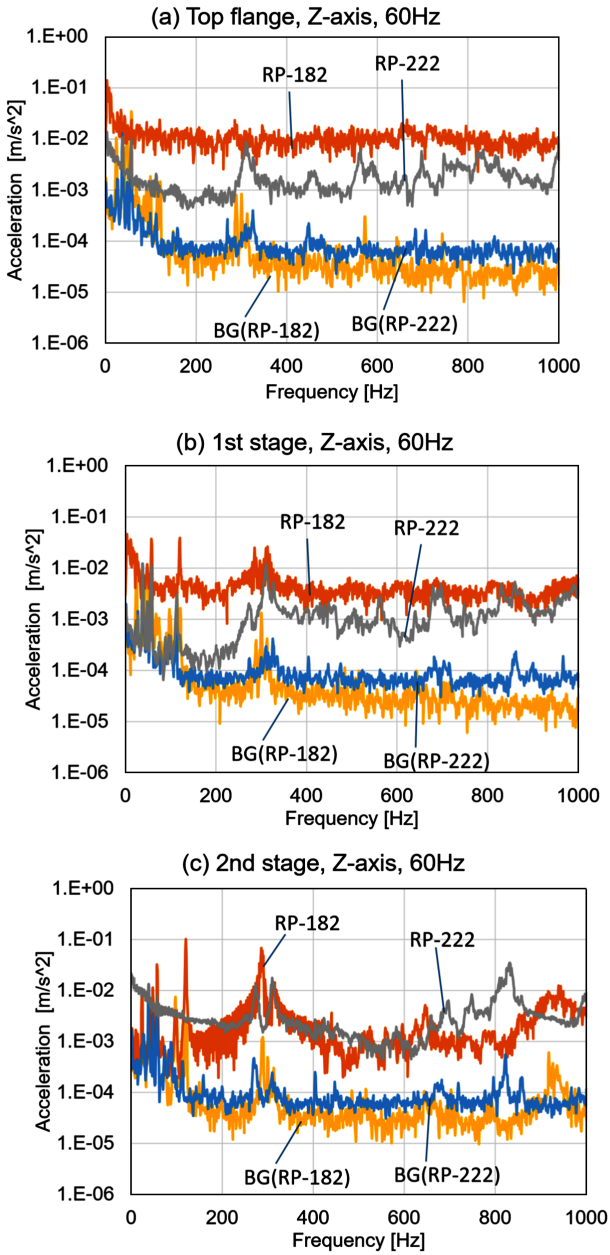

Figure 6. Acceleration of the RP-222B3S pulse tube refrigerator. BG represents the background vibration measurement of the anti-vibration table without running the pulse tube refrigerator.

temperature less than 2.8 K. It features two electrical isolators and a remote valve for vibration reduction. The refrigerator configuration is unchanged for both 50 and 60 Hz compressor operation, which is convenient for international users and developers.

With 50 Hz compressor operation, the refrigerator can provide 60 W at 48.0 K and 2.0 W at 4.05 K, and the no-load temperature is 2.54 K. For 60 Hz compressor operation, 60 W at 46.7 K and 2.0 W at 4.02 K, as well as the no-load temperature of 2.29 K are obtained with the same pulse tube refrigerator without any change. Fast cooldown, good precooling performance and low vibration are demonstrated by testing.

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