Development of High Cooling Capacity 3 K Two-Stage Pulse Tube Cryocooler

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ABSTRACT

The quantum computing and dilution refrigerator (DR) market is growing very rapidly, and development of high cooling capacity, ultra-low vibration, fast cool-down, energy efficient, and reliable cryocoolers for this market is of great importance. This application has the potential to become another major industrial market for cryocoolers. Higher cooling capacities are normally required at 3 K or below, rather than at 4.2 K, for most dilution refrigerators. Commercial 4 K cryocoolers (either pulse tube or G-M) are normally designed for optimum performance at 4.2 K. In addition to higher cooling capacities at 3 K, lower no-load temperatures are also required for this application. A high cooling capacity 3 K two-stage pulse tube cryocooler has been developed at Cryomech (Model: PT310), which can provide 1.0 W at 3.0 K on the 2nd stage with 35 W at 35 K on the 1st stage simultaneously, operating on either 60 or 50 Hz power. The no-load base temperature is lower than 2.30 K. The input powers are 13.0 kW (60 Hz) and 12.0 kW (50 Hz) at steady state. The cooling performance and experimental results will be presented in this paper.

INTRODUCTION

The quantum computing and dilution refrigerator (DR) market is growing very rapidly, and development of high cooling capacity, ultra-low vibration, fast cool-down, energy efficient, and reliable cryocoolers for this market is of great importance. This application has the potential to become another major industrial market for cryocoolers in the near term.

With the advantages of low vibration, high reliability and long mean time between maintenance, the two-stage pulse tube cryocooler is the preferred solution for providing pre-cooling capacity for dry dilution refrigerators.

However, higher cooling capacities are normally required at 3 K or below, rather than at 4.2 K, for most dilution refrigerators. Commercial 4 K cryocoolers (either pulse tube or G-M) are normally designed for optimum performance at 4.2 K. In addition to higher cooling capacities at 3 K, lower no-load temperatures are also required for this application.

In response to the market demand, Cryomech has developed a high cooling capacity 3 K two-stage pulse tube cryocooler (Model: PT310). This paper presents cooling performance and experimental results of the development.

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(a) (b)

Figure 1. PT310 pulse tube cryocoolers. (a) integrated motor, model PT310; (b) remote motor, model PT310-RM

SYSTEM DESIGN

Figure 1 shows the images of the PT310 and the PT310-RM two-stage pulse tube cryocoolers. The physical size of the PT310 expander is identical to Cryomech models PT420 (2.0 W/4.2 K) and PT425 (2.7 W/4.2 K), which allows for swap-and-switch implementation on existing customer designs.

There are two types of rotary valve integration: (a) standard design with the rotary valve/motor assembly integrated on the warm end of the pulse tube; (b) remote motor design with the rotary valve/motor assembly separated from the pulse tube. In the remote motor design, the rotary valve/motor assembly is connected to the pulse tube through a 24" or 36" long stainless-steel flexible line. Two reservoir volumes are also connected to the pulse tube through 24" long stainless-steel flexible lines.

The compressor for the system is Cryomech Model CPA1114 with power consumptions of 13.0 kW (60 Hz) and 12.0 kW (50 Hz) when the cold head is operating at steady state. The system static pressures are 240 psig (60 Hz) and 270 psig (50 Hz).

PERFORMANCE AND DISCUSSION

Cooling Capacity

Figures 2 and 3 show the typical cooling capacity curves of the PT310 minimum guaranteed cooling capacity of the PT310 is 1.0 W at 3.0 K on the 2nd stage with 35 W at 35 K on the 1st stage

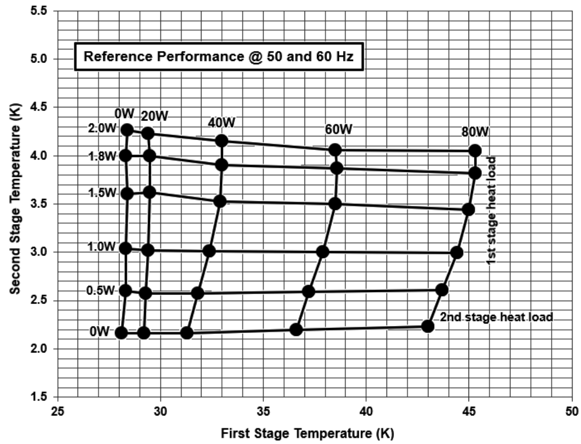

Figure 2. Typical cooling capacity curves of the PT310 pulse tube cryocooler.

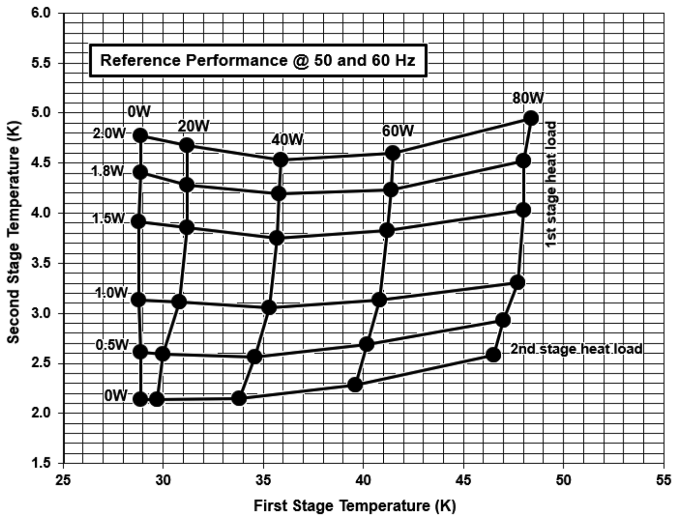

Figure 3. Typical cooling capacity curves of the PT310-RM pulse tube cryocooler.

simultaneously, operating on either 60 or 50 Hz power, respectively. The minimal guaranteed cooling capacity of the PT310-RM is 0.9 W at 3.0 K on the 2nd stage and 32 W at 35 K on the 1st stage simultaneously, operating on either 60 or 50 Hz power. The guaranteed no-load base temperature of the 2nd stage for both models is less than 2.3 K.

The 1st stage temperature is measured using a silicon diode sensor, while the 2nd stage temperature is measured using a calibrated Cernox RTD sensor having a calibrated accuracy of ±5 mK from 1.4 to 4.2 K.

The cooling capacities of the PT310-RM from its base temperature to 3.0 K were measured. The 1st stage temperature was maintained at 35 K throughout the testing.

Figure 4 shows the cooling capacity curves of an experimental remote motor unit (PT310-RM) up to 3 K. It indicates a no-load base temperature of 2.17 K with a cooling power greater than 0.5 W at 2.6 K.

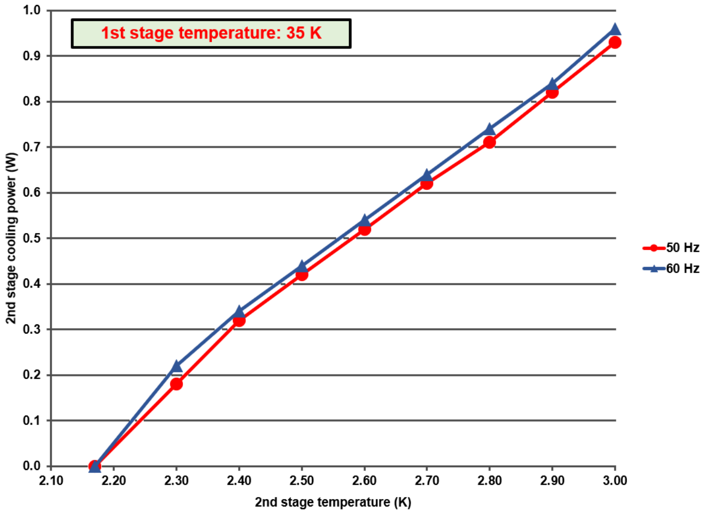

Figure 4. Cooling capacity curves of the 2nd stage of an experimental unit (PT310-RM) up to 3.0 K.

Cold Head Cool-down Speed

Cool-down speed testing was conducted on a PT310-RM. A constant heating power of 35 W is applied to the 1st stage, while a constant heating power of 0.90 W is applied simultaneously to the 2nd stage during cold head cool-down from room temperature. The schematic diagram of the experimental setup for the cool-down speed test of the PT310-RM is shown in Figure 5.

The cool-down curves are shown in Figure 6. With heat loads of 35 W and 0.90 W applied to the 1st stage and 2nd stage simultaneously, it takes about 85 minutes for the 1st stage to reach 35 K and about 60 minutes for the 2nd stage to reach 3.0 K.

Regenerator Intermediate Cooling Capacity

In pulse tube cryocoolers, additional cooling is available as distributed cooling along the pulse tube and regenerator or as intermediate cooling at a certain location on the pulse tube and regenerator. Research and investigations on extracting cooling from the 2nd stage pulse tube and regenerator in two-stage 4 K pulse tube cryocoolers have been conducted by Wang.[1, 2]

Distributed cooling from the regenerator was first used for precooling helium gas to be liquefied in a small helium liquefaction system using a 4 K pulse tube cryocooler. [3] A small stainless-steel tube is thermally anchored to the 2nd stage regenerator to precool the helium gas to be liquefied. Numerical analysis and an experimental test of distributed cooling was performed by Wang. [4] Distributed cooling significantly increases the helium liquefaction rate.

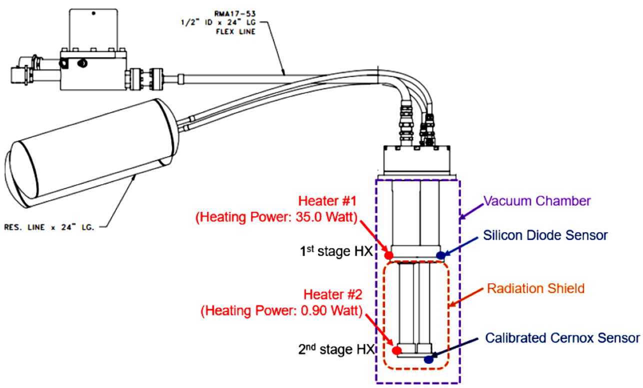

Figure 5. Schematic diagram of the experimental setup for the cool-down speed test of a PT310-RM.

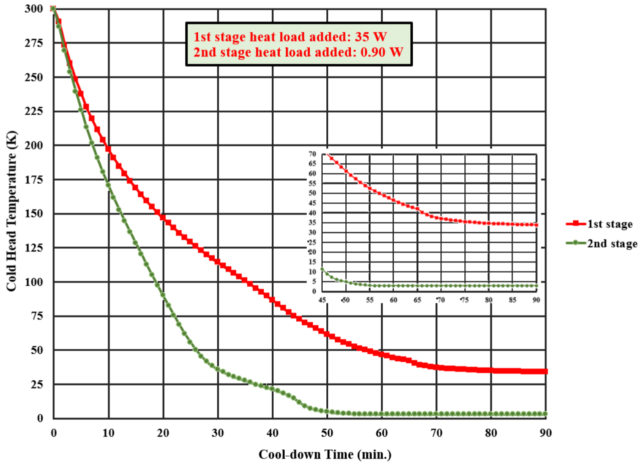

Figure 6. Cool-down curves of a PT310-RM cryocooler operating on 60 Hz.

Intermediate cooling is extracted from a certain location on the 2nd stage regenerator or the 2nd stage pulse tube. This paper introduces the results of extracting intermediate cooling from the 2nd stage regenerator on an experimental unit (PT310-RM).

The experimental set-up for extracting intermediate cooling from the 2nd stage regenerator is shown in Figure 7.

The intermediate heat exchanger (HX) is mounted on the 2nd stage regenerator tube. The heat exchanger is made of OFHC copper and has good thermal contact with the regenerator tube. A calibrated silicon diode temperature sensor and a resistive heater are mounted on the intermediate HX for temperature and cooling capacity measurement.

The cooling capacities of the intermediate HX mounted at different locations along the regenerator have been measured. The test results of the intermediate HX (HX center) located at a height of 38% of the total length of the regenerator, measured from the cold end, are presented in this paper.

In the test, the 1st and 2nd stage temperatures are maintained at 35 K and 3.0 K using PID control. Heat loads from 0 to 3.25 W are applied to the intermediate HX. The intermediate HX can provide 3.22 W of cooling at 9.0 K without affecting the 2nd stage cooling capacity at 3.0 K. However, the 1st stage cooling capacity drops from 40.5 W to 18.3 W at 35 K, as shown in Figure 8.

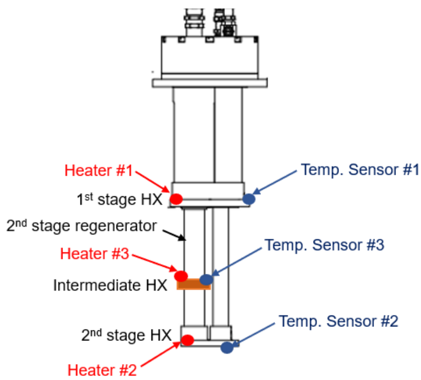

Figure 7. Schematic for extraction of intermediate cooling from the 2nd stage regenerator.

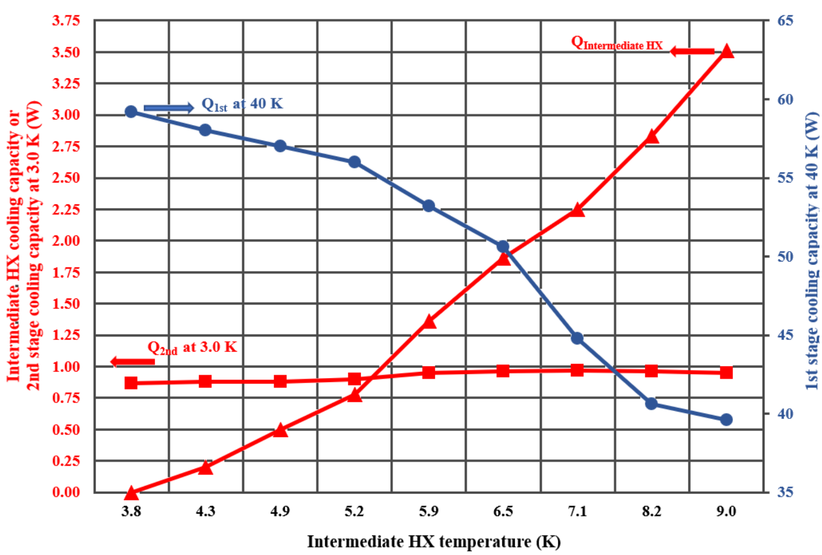

Figure 8. Cooling capacity of the intermediate HX with the 1st stage at 35 K and 2nd stage at 3.0 K.

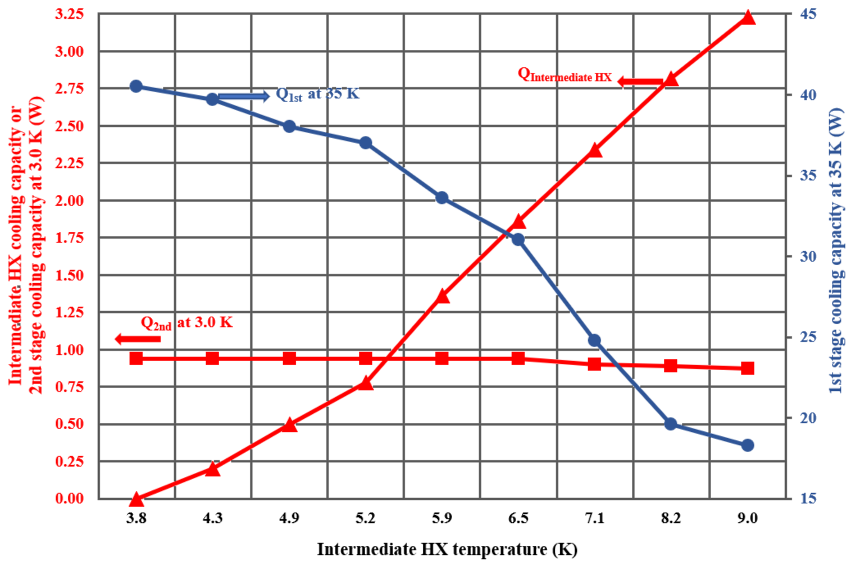

Figure 9. Cooling capacity of the intermediate HX with the 1st stage at 40 K and 2nd stage at 3.0 K.

The 1st stage temperature is then increased and maintained at 40 K, while the 2nd stage temperature is still maintained at 3.0 K. Heat loads from 0 to 3.6 W are applied to the intermediate HX. The intermediate HX can provide 3.51 W of cooling at 9.0 K without affecting the 2nd stage cooling capacity at 3.0 K. The 1st stage cooling capacity drops from 59.2 W to 39.6 W at 40 K, as shown in Figure 9.

The degradation of the 1st stage cooling capacity at 35 K or 40 K can be improved by adjusting the location of the intermediate HX along the regenerator. The test results of the intermediate HX located at a height of 38% of the total length of the regenerator, measured from the cold end, are presented in Figure 9 for illustration and reference only.

CONCLUSIONS

A high cooling capacity 3 K two-stage pulse tube cryocooler has been developed at Cryomech, Inc. It has been developed to deliver optimum heat lift performance at 3 K and below, which enables dry dilution refrigerators to achieve improved cooling performance at temperatures in the millikelvin range. The PT310 cryocooler can provide 1.0 W at 3.0 K on the 2nd stage with 35 W at 35 K on the 1st stage simultaneously, operating on either 60 or 50 Hz power. The input powers are 13.0 kW (60 Hz) and 12.0 kW (50 Hz) at steady state.

As part of its development, the PT310 cryocooler went through consistency tests to ensure reliable performance. The PT310 cryocooler has the same envelope as the Cryomech PT425 cryocooler (2.7 W/4.2 K), which makes for an easy fit to the next generation of dilution refrigerators.

ACKNOWLEDGMENT

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REFERENCES

1. Wang, C., "Development and Application of Low Frequency Pulse Tube Cryocooler," *Proc. Of ICCR' 2008*, Science Press, Beijing (2008), pp. 61-70.

2. Wang, C., "Extracting Cooling from the Pulse Tube and Regenerator in a 4 K Pulse Tube Cryocooler," *Cryocooler 15*, ICC Press, Boulder, Colorado (2009), pp. 177-184.

3. Thummes, G., Wang, C. and Heiden, C., "Small Scale 4 He Liquefaction Using a Two-stage 4K Pulse Tube Cooler," *Cryogenics*, Vol. 38 (1998), pp.337-342.

4. Wang, C., "Helium Liquefaction with a 4 K Pulse Tube Cryocooler," *Cryogenics*, Vol. 41 (2001), pp.491-496.