Development of High Cooling Capacity and High Efficiency 4.2 K Pulse Tube Cryocoolers

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ABSTRACT

Cryomech has been continuously improving both cooling capacity and energy efficiency of its 4.2 K two-stage pulse tube cryocoolers. The model PT425, which was launched in March 2021, provides minimum cooling capacities of 2.7 W at 4.2 K on the 2nd stage with 55 W at 45 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. Its optimized design is based on the existing model PT420 (2.0 W at 4.2 K), without increasing the cryocooler's physical size and compressor model. It allows for swap-and-switch implementation on existing customer designs.

In this paper, both the cooling performance and experimental results will be reported. The effects on cooling performance when operating the PT425 at tilt angles up to 50° are also reported.

INTRODUCTION

With broad applications in low temperature superconductors, medical devices (MRI, NMR, MEG), helium liquefaction, dry dilution refrigerators, ADRs, 4 K dry cryostats, 1 K systems, telescopes, scientific instruments and physical research, the development of high cooling capacity, and reliable 4.2 K two stage cryocoolers is of great importance.

Extensive research and numerous investigations have been carried out on pulse tube cryocoolers since their invention in 1964 due to their inherent advantages of low vibration, high reliability, and long mean time between maintenance. Cryomech has been continuously improving the cooling capacities of its 4.2 K two-stage pulse tube cryocoolers. The 2.0 W at 4.2 K two stage pulse tube cryocooler (Model PT420) was developed and introduced by Cryomech in 2016, which, at the time, was the largest, commercially available, 4 K pulse tube cryocooler. [1]

Recently, by optimizing regenerator design, cold side heat exchanger design, reservoir size and operating conditions, the cooling capacities are significantly improved without increasing the cryocooler's physical size and compressor model. The newly developed model PT425 was launched in March 2021 and provides a minimum of 2.7 W at 4.2 K on the 2nd stage with 55 W at 45 K on the 1st stage simultaneously, operating on either 60 or 50 Hz power.

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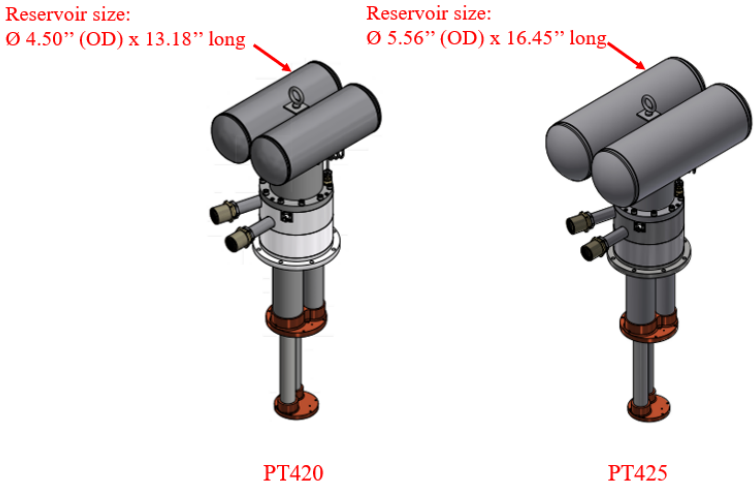

Figure 1. Images of the PT420 and the PT425 pulse tube cryocoolers.

SYSTEM DESIGN

Figure 1 shows the images of the PT420 and the PT425 two-stage pulse tube cryocoolers. The physical dimensions of the PT420 cold finger are identical to the PT425 cold finger, which allows for swap-and-switch implementation on existing customer designs. The only physical difference between the two models is the size of the room temperature reservoirs, which increased from Ø 4.50" x 13.18" long (PT420) to Ø 5.56" x 16.45" long (PT425).

Like the PT420, there are two types of rotary valve integrations available for the PT425: (a) Standard design with the rotary valve/motor assembly integrated on the warm end of the pulse tube, model name: PT425; (b) Remote motor design with the rotary valve/motor assembly separated from the pulse tube, model name: PT425-RM. 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 stainless-steel flexible lines.

The same helium compressor (Cryomech Model CPA1114) is used for the PT420's and PT425's operation. The motor/rotary valve speed (RPM) of the two cryocoolers is also the same.

PERFORMANCE AND DISCUSSION

Cooling Capacity

Figures 2 and 3 show the typical cooling capacity curves of the PT425 and the PT425-RM, respectively. The minimal guaranteed cooling capacity of the PT425 is 2.7 W at 4.2 K on the 2nd stage with 55 W at 45 K on the 1st stage simultaneously, operating on either 60 or 50 Hz power. The minimal guaranteed cooling capacity of the PT425-RM is 2.35 W at 4.2 K on the 2nd stage with 50 W at 45 K on the 1st stage simultaneously, operating on either 60 or 50 Hz power. The guaranteed no-load base temperature of the 2nd stage is 2.8 K.

The 1st stage temperature is measured using a non-calibrated silicon diode sensor, while the 2nd stage temperature is measured using a calibrated silicon diode sensor having a calibrated accuracy of ±12 mK at 4.2 K.

Cold Head Cool-down Speed

The cool-down speed from room temperature to base temperature has been measured on a PT425-RM. A constant heating power of 50 W is applied to the 1st stage, while a constant heating power of 2.35 W is applied to the 2nd stage simultaneously during cold head cool-down from room

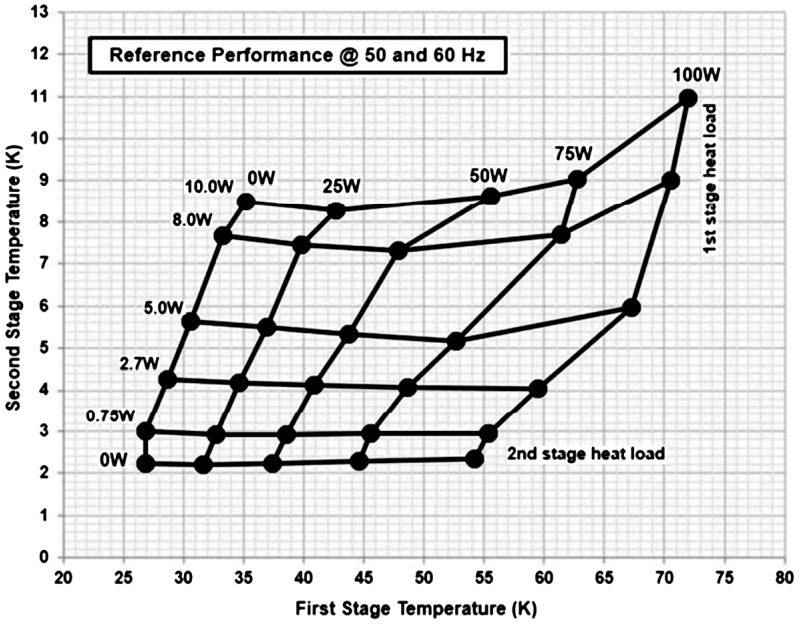

Figure 2. Typical cooling capacity curves of the PT425 pulse tube cryocooler.

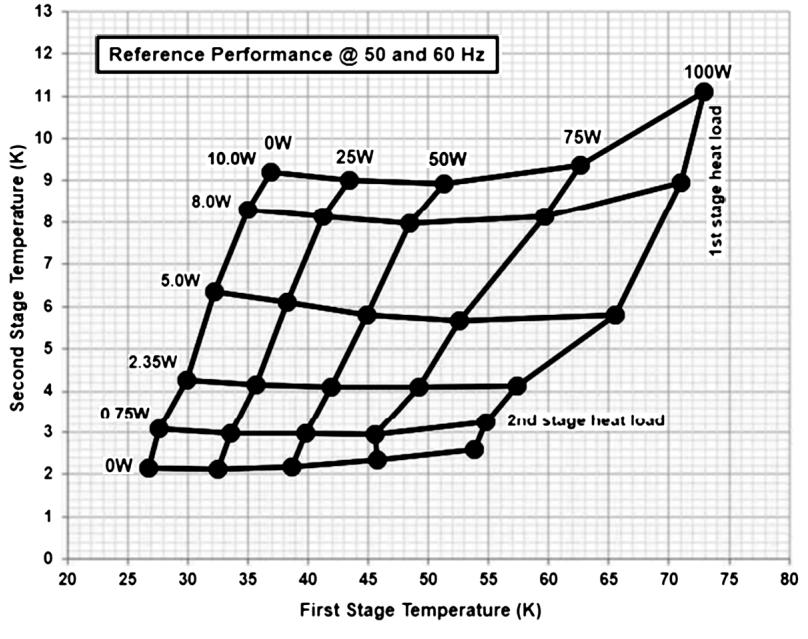

Figure 3. Typical cooling capacity curves of the PT425-RM pulse tube cryocooler.

temperature. The schematic diagram of the experimental setup of the PT425-RM cool-down speed testing is shown in Figure 4.

The cool-down curves are shown in Figure 5. With heat loads of 50 W and 2.35 W applied to the 1st stage and 2nd stage simultaneously, it takes about 90 minutes for the 1st stage to reach 45 K and about 70 minutes for the 2nd stage to reach 4.2 K.

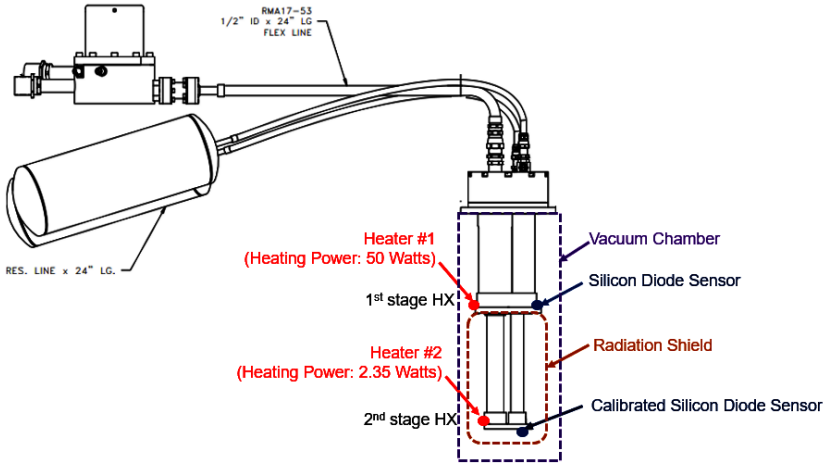

Figure 4. Schematic diagram of the experimental setup of the PT425-RM cool-down speed testing.

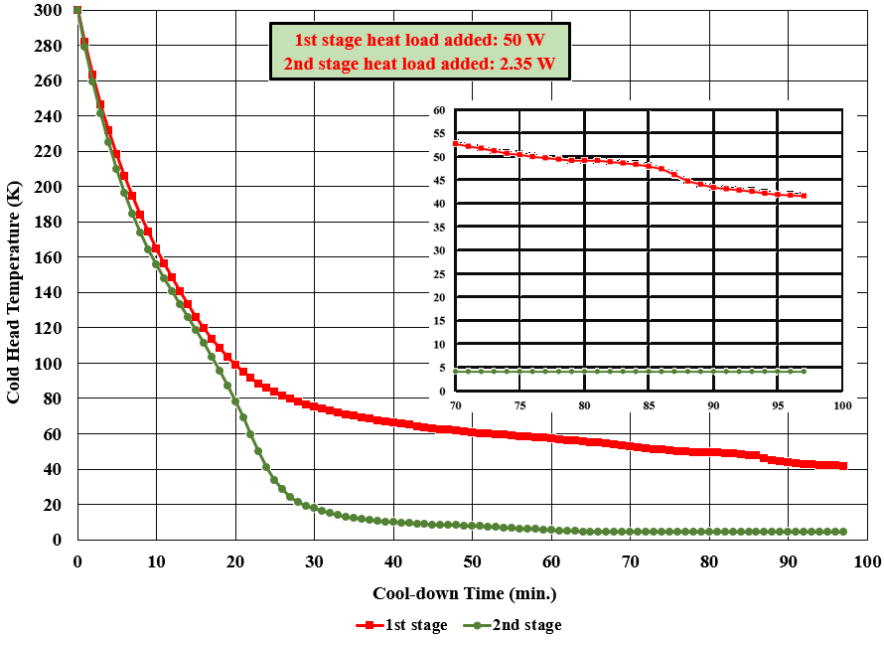

Figure 5. Cool-down curves of a PT425-RM cryocooler (60 Hz).

Cold Head Orientation Dependence

The helium gas in the pulse tube is subject to heat transfer by convection which occurs in fluids. In the normal operating mode at vertical orientation (cold end tip-down), the gas column reaches an equilibrium with a thermal gradient from the top to the bottom of the gas column with minimal convective mixing. Once the pulse tube cryocooler is tilted from the vertical, convective processes disrupt the thermal gradient, which reduces the efficiency of the cooling cycle. Therefore, the performance of a pulse tube cryocooler is tied to the tilt angle of the system relative to the gravity vector. The cooling capacity decreases as a function of the tilt angle. [2] The gravitational effect of

the gas on the cooling performance of G-M type and Stirling type pulse tube cryocoolers has been experimentally and numerically studied many times in the past. [3-5]

Gravitational effect testing has been conducted on an experimental PT425-RM. The tilt angles range from 0° (vertical) to 50° as shown in Figure 6.

The actual cooling capacity of this experimental PT425-RM operating in a vertical orientation is 2.64 W at 4.2 K on the 2nd stage with 62.4 W at 45 K on the 1st stage simultaneously with 60 Hz power. The actual power consumption is 12.8 kW when the pulse tube is operating at steady state with the fore-mentioned heat loads applied.

In the testing, the 1st and 2nd stage temperatures are maintained at 45 K and 4.2 K using PID control. The cooling capacities of the 1st stage at 45 K and the 2nd stage at 4.2 K, diminishing over increasing tilt angles, are presented in Figure 7.

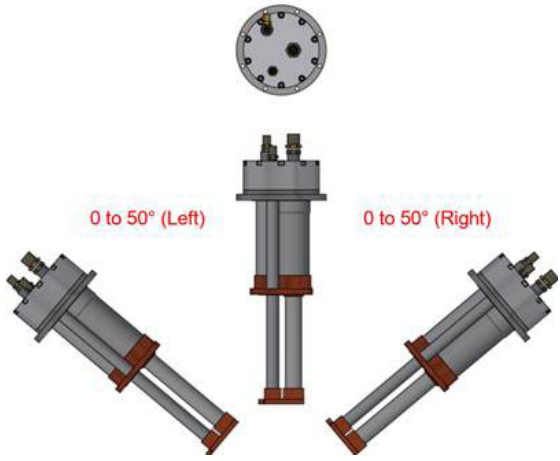

Figure 6. Schematic of the tilt angles of the PT425-RM in gravitational effect testing.

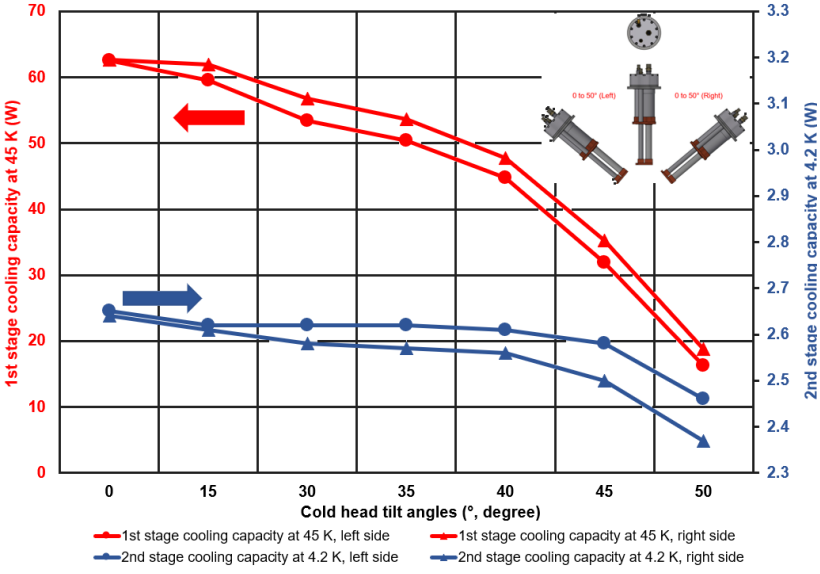

Figure 7. Cooling capacities of 1st and 2nd stages changing over tilt angles.

The 1st stage cooling capacity of the PT425-RM at 45 K is highly orientation dependent, especially when the tilt angle is larger than 40°. The cooling capacity dramatically decreases with tilt angles increasing above 40°. The cooling capacity degradation from vertical orientation (0°) to 40° at 45 K is approximately 15 to 18 W.

However, the effect of tilt angles on the 2nd stage cooling capacity at 4.2 K is slight, especially when the tilt angle is smaller than 40°. The cooling capacity degradation at 4.2 K from vertical orientation (0°) to 40° is less than 0.1 W. The physical sizes of the 1st stage pulse tube and regenerator are larger than the 2nd stage; one of the major reasons why the cooling performance of the 1st stage is affected more by gas gravity, and more orientation dependent than the 2nd stage.

CONCLUSIONS

A high cooling capacity 4.2 K two-stage pulse tube cryocooler (Model PT425) has been developed at Cryomech. The PT425 cryocooler provides a minimally guaranteed 2.7 W at 4.2 K on the 2nd stage with 55 W at 45 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 PT425 cryocooler went through consistency tests to ensure reliable performance.

REFERENCES

1. Wang, C., “A 4 K Pulse Tube Cryocooler with Large Cooling Capacity,” *Cryocooler 19*, ICC Press, Boulder, CO (2017), pp. 299-305.
2. Tsan, T. et al., “The Effects of Inclination on A Two Stage Pulse Tube Cryocooler for Use with A Ground Based Observatory,” *Cryogenics*, Vol.117 (2021).
3. Ross Jr, R.G., Johnson, D.L., “Effect of Gravity Orientation on the Thermal Performance of Stirling-type Pulse Tube Cryocoolers,” *Cryogenics*, Vol.44 (2004), pp.403-408.
4. Yang, L., Thummes, G., “Performance Characteristics in Tilted Pulse Tube Refrigerators,” *Proceedings of ICEC23-ICMC* 2010, (2010), pp. 235-241.
5. Fang, T. et al., “Investigation of Gravitational Effects in Pulse Tube Cryocoolers Using 3-D CFD Simulations,” *Cryocooler 19*, ICC Press, Boulder, Colorado (2016), pp. 183-192.