A Novel Three-Stage 4 K Pulse Tube Cryocooler

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ABSTRACT

A three-stage pulse tube cryocooler has been successfully developed at Cryomech, Inc. to provide cooling capacities at temperatures around 45 K, 15 K and 4 K. Unlike a conventional staged pulse tube cryocooler, this three-stage pulse tube cryocooler uses a middle bypass to build the 2nd stage cooling station. This design allows us to use parts from our two-stage pulse tube cryocooler, such as the ambient temperature phase shifters, and heat exchangers. The new design makes the cold head more compact and simplifies manufacturing. The three-stage pulse tube cryocooler reaches temperatures of 29.3 K, 8.7 K and 2.38 K on three stages in 74 min. It can provide 37 W at 45 K, 15 W at 15 K and 0.3 W at 3.97 K simultaneously with an input power of 11.0 kW.

INTRODUCTION

The 4 K pulse tube cryocooler is a new generation of cryo-refrigeration system that can provide cooling below 4 K. Cryomech, Inc. has developed and commercialized a series of two-stage 4 K pulse tube cryocoolers that provide cooling capacity from 0.25 W to 1.5 W at 4.2 K. The 4 K pulse tube cryocoolers has demonstrated some significant advantages over Gifford-McMahon (G-M) cryocoolers in many challenging applications.[1]

Some applications require three cooling stations at temperatures of ~45 K, ~15 K, and 4 K. Cryomech, Inc. is partially funded by a customer to develop a three-stage 4 K pulse tube cryocooler to meet their requirements.

There are many configurations to design multistage pulse tube cryocoolers. Three popular staged designs are listed in Figure 1. A feature of the Type A design in Figure 1 is the two-stage pulse tube extending to the room temperature. Its hot heat exchanger is thermally connected to the room temperature heat sink.[2,3] Gas flow in the 1st and the 2nd stage can be conveniently controlled at room temperature. TheType B design in Figure 1 has separated the 1st and- 2nd stage regenerators. The middle of the 2nd stage regenerator is cooled by the 1st stage cooling station through a thermal bridge.[4,5,6] This design reduces an interaction of flow controls for the 1st and the 2nd stage. In a Type C configuration, the warm end and 2nd stage phase shifters are thermally anchored to the 1st stage cooling station.[7,8] The Type C design has cryogenic phase shifter and can control the 2nd stage flow more efficiently than the Type A and Type B designs. However, the 2nd stage pulse tube pumps heat to the 1st stage cooling station.

These three types of designs increase the complexity for building the three-stage pulse tube cryocooler, and results in difficulty in manufacturing and system testing. Therefore, we have

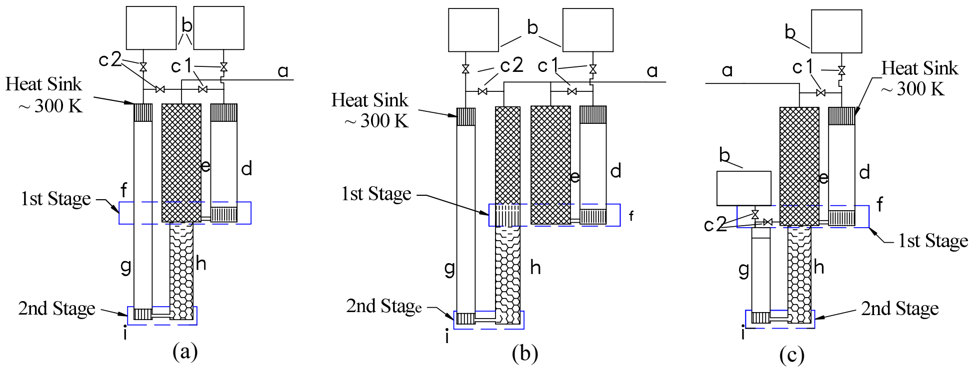

Figure 1. Popular staging designs for two-stage pulse tube cryocoolers, a: connecting line to pressure wave generator; b:1st and 2nd stage reservoirs; c1,c2: 1st sand 2nd stage orifices; d: 1st stage pulse tube; e: 1st stage regenerator; f: 1st stage cooling station; g: 2nd stage pulse tube; h: 2nd stage regenerator; i: 2nd stage cooling station.

developed a unique configuration for this three-stage pulse tube cryocooler, Cryomech Model PT3S403. This paper introduces its principle design and performance.

PRINCIPLE DESIGN OF THE PT3S403

The three-stage pulse tube cryocooler is designed to use most parts of our PT410, such as the room temperature phase shifters, heat exchangers and the 1st stage regenerator. A middle bypass, which is shown in Figure 2, is used to build the second cooling station. The middle-bypass between the regenerator and the pulse tube has two effects on the refrigeration process: precooling at the middle connection, and shifting the phase of refrigerant flow.[9] The middle-bypass can be used

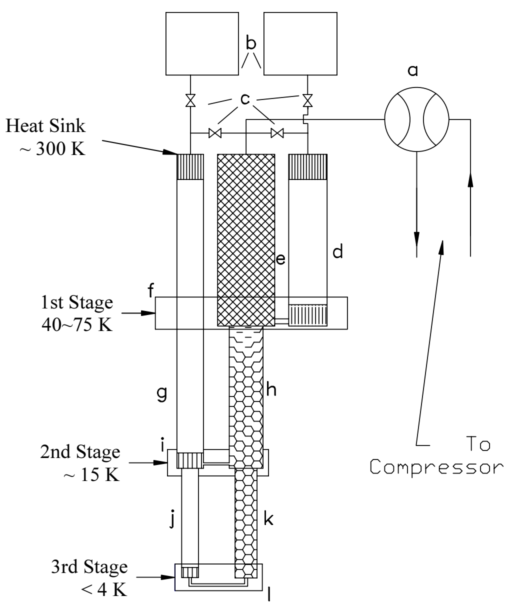

Figure 2. Schematic of the PT3S403, a: rotary valve; b:1st and 2nd stage reservoir; c: 1st and 2nd stage; d: 1st stage pulse tube; e: 1st stage regenerator; f: 1st stage cooling station; g: 2nd stage pulse tube; h: 2nd stage regenerator; i: 2nd stage cooling station; j: 3rd stage pulse tube; k: 3rd stage regenerator: l: 3rd stage cooling station.

Figure 3. Photo of the PT3S403

to design either a multi-stage pulse tube with its precooling and expansion, or a single-stage pulse tube by the aid of the phase shifting. Based on the author's theoretical analysis, the 2nd stage in this design will provide enough cooling capacity for most applications.

This novel design not only saves developing time by using most of the parts of PT410, but also is convenient for the product manufacturing. Figure 3 is a photo of prototype of the three-stage pulse tube cryocooler.

A CP1014 compressor package was available at Cryomech, Inc. and was first used for this development. The compressor module is a Copeland scroll compressor, model ZCH125 (ZCH94). We found that this module was too big to drive the PT3S403 cold head, and has lower efficiency in its operating pressure. All results in this paper were obtained with the CP1014 compressor package. In the future, a newly designed compressor package, model CP1010 will be used for this three-stage pulse tube cryocooler.

PERFORMANCE OF PT3S403

The system works successfully and all three stages can reach their desired temperature. The performance of the three stages of the PT3S403 is optimized at different frequencies. Figure 4 shows the cooling performances at different frequencies while three stages were applied with a simultaneous heat load. The optimum frequency for the 1st and 3rd stages is 1.8 Hz,. For the 2nd stage, it is 2.0 Hz. We selected 1.8 Hz as the operating frequency for the three-stage pulse tube cryocooler. This frequency is higher than our two-stage 4 K pulse tube cryocoolers (1.4 Hz). The following results are obtained at an operating frequency of 1.8 Hz.

The cool down time of the PT3S403 is shown in Figure 5. The 1st stage takes 74 min to reach a temperature of 29.3 K, and the 2nd stage takes 46 min to reach 8.7 K. The 3rd stage reaches 4 K in 43 min and the bottom temperature of 2.38 K in 58 min. The cool down times to reach the bottom temperatures are very close to our two-stage 4 K pulse tube cryocoolers.

The three-stage pulse tube cryocooler has been continuously operated for three weeks to test its stability. The temperatures on the three cooling stations are given in Figure 6 (a), (b) and (c).

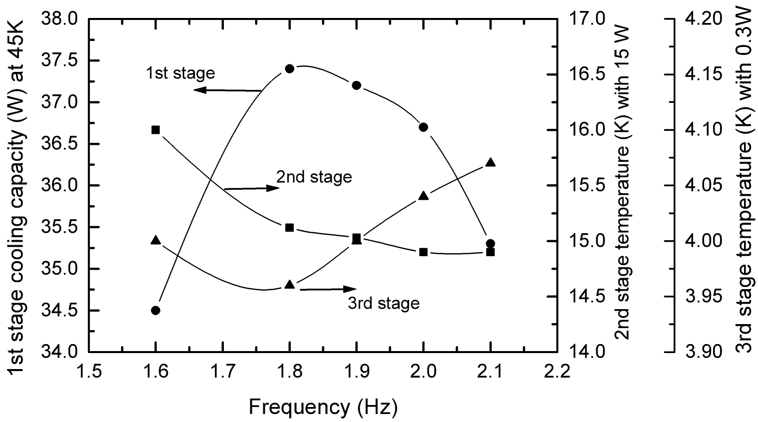

Figure 4: Cooling Performance of the PT3S403 at Different Frequencies.

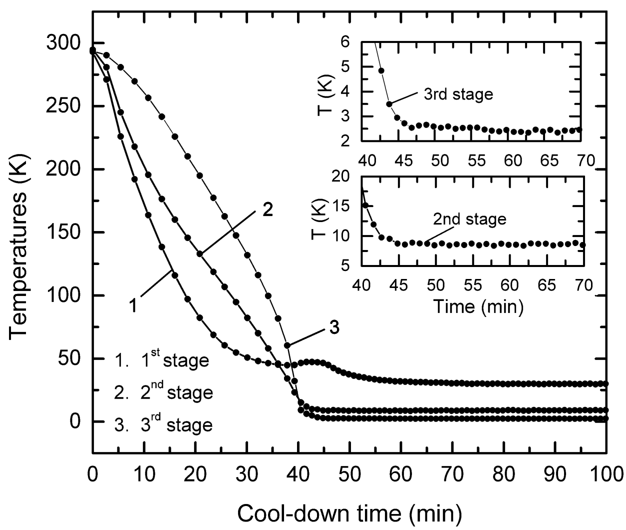

Figure 5. Cool down speed of the PT3S403

During the test, a heat load of 37 W is applied to the first stage by a temperature controller. DC power supplies were used to apply heat loads to the 2nd and 3rd stages. Since the heat load of 15 W is applied to the 2nd stage without temperature control, the heater could burn the cold head if compressor power failed or cold head stopped during the night. Therefore, the 2nd stage heater was only turned on during-daytime working hours. Section 1 in Figure 6 is the temperatures without heat loads on three stages. Section 2 is obtained when the 1st stage has a heat load of 37 W applied, the 2nd stage has no heat load, and the 3rd stage has a heat load of 0.3 W. Section 3 is obtained when the 1st stage has a load of 37 W, the 2nd stage has a load of 15 W, and the 3rd stage has a load of 0.3 W. The three-stage pulse tube cryocooler demonstrates stable operation during all tests. Slight variations in the temperatures could be caused by environment temperature or small fluctuation in the heat loads.

Figure 7 shows a cooling load map of the 1st and 2nd stages while there is a heat load of 0.3 W on the 3rd stage. The 1st stage performance decreases when the 2nd stage temperature increases from 8.7 K to 15 K. The 1st stage performance starts to increase when the 2nd stage temperature is over 15 K. The 2nd stage performance decreases with increasing 1st stage temperature.

Figure 8 shows a cooling load map of the 2nd and 3rd stage when there is a heat load of 37 W on the 1st stage. Higher 2nd stage temperatures result in less cooling capacity at the 3rd stage of 4.2 K. The three-stage pulse tube cryocooler provides 37 W at 45 K on the 1st stage, 15 W at 15 K on the

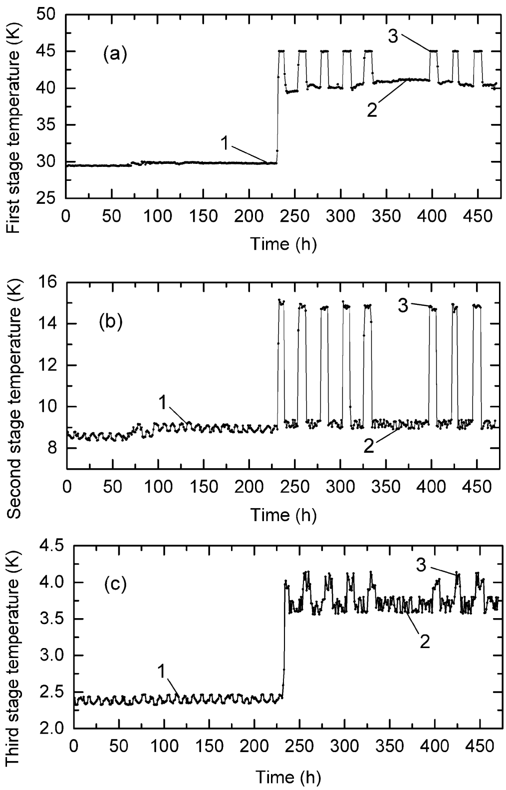

Figure 6. Three Week Stability Test of PT3S403, 1. no loads on three stages; 2. 37 W on the 1st stage, no load on the 2nd stage, 0.3 W on the 3rd stage; 3. 37 W on the 1st stage, 15 W on the 2nd stage, 0.3 W on the 3rd stage.

2nd stage and 0.3 W at 3.97 K on the 3rd stage with an input power of 11.0 kW. It can also provide 48 W at 50 K, 19 W at 22 K and 0.3 W at 4.06 K with 11.3 kW of input power.

FUTURE WORK

The three-stage pulse tube cryocooler consumed a higher electrical power consumption than expected. By investigating mass flow rate and power consumption of compressors, we found that the CP1014 compressor module, Copeland model ZCH125, has lower efficiency in the operating pressure of the PT3S403.

Table 1 compares the mass flow rates and power consumptions of three compressor packages from Cryomech, Inc., model CP970, CP1010 and CP1014. The three compressors in the comparison operate at the same suction pressure of 654 kPa, and discharge pressure of 2030 kPa. The comparison shows that the larger scroll compressor has a lower compression efficiency. Our newly developed CP1010 compressor will be used as the compressor to drive the PT3S403. The power consumption of the PT3S403 should drop to ~10 kW.

Some applications require more cooling capacity on the 3rd stage. The three-stage pulse tube cryocooler will be redesigned to shift the cooling capacities on the three stages to meet different applications.

CONCLUSION

A middle bypass was successfully used to build a second cooling station in a three-stage pulse tube cryocooler. This novel three-stage pulse tube cryocooler can provide cooling capacities of

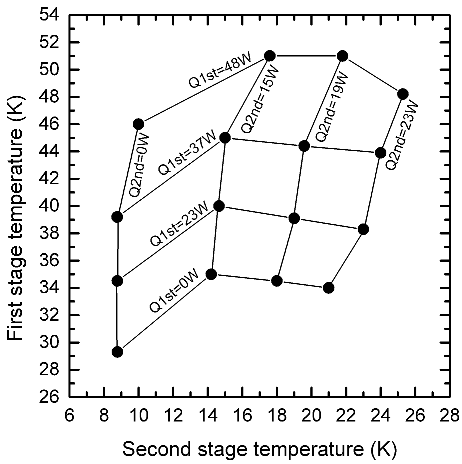

Figure 7. Cooling load map of the 1st and 2nd stages, the 3rd stage is at the temperature ~ 4 with 0.3 W.

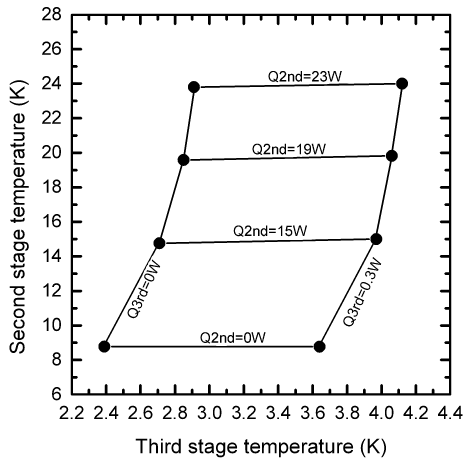

Figure 8. Cooling load map of the 2nd and 3rd stages, the 1st stage is at temperatures from 39 K to 45 K with 37 W.

Table 1. Comparison of three compressor packages.

Model	Mass flow rate, $\dot{m}$	Power consumption, W	Efficiency, $\dot{m}/W$
CP970	5.0 g/s	6.89 kW	0.73
CP1010	7.0 g/s	10.40 kW	0.67
CP1014	8.6 g/s	14.58 kW	0.59

37 W at 45 K, 15 W at 15 K and 0.3 W at 3.96 K simultaneously with 11 kW power input. Its system efficiency could be improved by using our newly developed compressor package, model CP1010.

ACKNOWLEDGMENT

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