Extracting Cooling from the Pulse Tube and Regenerator in a 4 K Pulse Tube Cryocooler

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ABSTRACT

This paper introduces extractive cooling from the 2nd stage pulse tube and regenerator in a two-stage 4 K pulse tube cryocooler. Excess cooling can be distributed cooling along the pulse tube and regenerator or intermediate cooling at a certain location on the pulse tube and regenerator. The 2nd stage pulse tube provides significantly more capacity of distributed cooling than the regenerator with less effect of cooling performance on both stages. Two intermediate heat exchangers mounted on the 2nd stage pulse tube and regenerator can provide cooling capacities of 0.5 W to 3.5 W at temperatures between 6.5 K to 26 K without affecting the 2nd stage performance. Extracting cooling from the pulse tube and regenerator decreases the first stage cooling performance.

INTRODUCTION

Due to the development advances in the past decades, pulse tube cryocoolers have been successfully commercialized and opened many challenging applications in cooling superconducting devices, low temperature electronic devices, etc. They demonstrate advances of high reliability, long meantime between maintenance and extra low vibration over the traditional Gifford-McMahon (G-M) and Stirling cryocoolers in the field.[1,2]

The 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. It is also successfully used for cryogen- free dilution refrigerators to precool ^{3}He and results in improvement of performance.[5,6]

Regenerator behavior for a single stage cryocooler with heat input or removal at intermediate temperatures was theoretically analyzed by Radebaugh, et al.[7] Zhu, et al.[8] theoretically analyzed excess cooling by adding a heat exchanger inside of the 2nd stage regenerator in a 4 K pulse tube cryocooler. After discussion with a group at Air Liquide DTA, Cryomech, Inc. designed and manufactured a 4 K pulse tube cryocooler for Air Liquide DTA with a heat exchanger inside of the 2nd stage regenerator. The results have been presented by Ravex, et al.[9]

Extracting cooling from the 2nd stage pulse tube in a 4 K pulse tube cryocooler was suggested by Wang.[10] Normally there is no heat input or removal on the pulse tube wall. The wall absorbs and

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dissipates the same amount of heat from/to the working gas in a compression/expansion cycle. It has a nonlinear temperature distribution along the wall of the 2nd stage pulse tube. The 2nd stage pulse tube is able to provide the excess cooling.

This paper introduces the results of extracting distributed cooling and intermediate cooling not only from the 2nd stage regenerator, but also from the 2nd stage pulse tube in a commercial 4 K pulse tube cryocooler. The performances of the intermediate heat exchangers on the 2nd stage pulse tube and regenerator have been presented.

EXPERIMENTAL SET UP

Distributed cooling is extracted along the entire length of the 2nd stage regenerator or the low temperature portion of the 2nd stage pulse tube. Intermediate cooling is extracted from a certain location on the 2nd stage regenerator and the 2nd stage pulse tube. In current research, it is extracted from both the regenerator and pulse tube via two joint heat exchangers. All experimental tests are performed using a two-stage 4 K pulse tube cryocooler, Cryomech Model PT410. The PT410 normally provides > 1 W at 4.2 K and >40 W at 40 K simultaneously while consuming ~7.5 kW of electrical power.

Figure 1 shows the experimental set up for extracting distributed cooling separately from the regenerator and pulse tube of the PT410 pulse tube cryocooler. A 48 manganin wire (a) is coiled evenly along the low temperature portion of the 2nd stage pulse tube (5) with a total of 16 turns. Another 75 manganin wire (d) is coiled evenly along the 2nd stage regenerator (7) with a total of 20 turns. Mylar tape is used to hold the manganin wires tightly on the surface of the pulse tube and regenerator. Cooling capacities of the distributed cooling are measured by using a ac power supply to apply a current through the manganin wires. All heat loads are measured with 4-wire configuration. Two calibrated silicon diode temperature sensors (b) and (e) are mounted on the first (4) and second (6) stage cooling stations. Two resistive heaters (c) and (f) are used to measure the cooling capacities of both stages.

The experimental set up for extracting the intermediate cooling is shown in Figure 2. Two intermediate heat exchangers HE1 (g) and HE2 (i) are soldered to the 2nd stage regenerator (7) and pulse tube (5). Each intermediate heat exchanger is made of a single piece and can extract cooling simultaneously from both the pulse tube and regenerator. The centers of HE1 and HE2 are located at 26% and 53% of the regenerator measured from the cold end. Two copper heat exchangers (h)

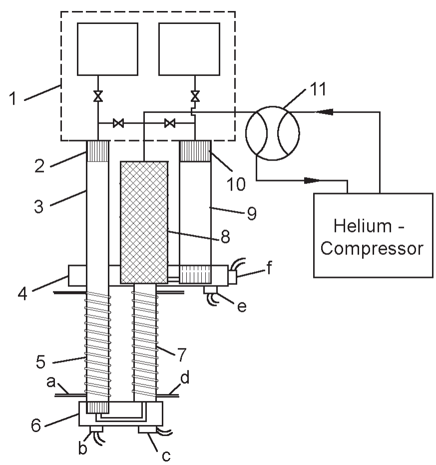

Figure 1. Schematic for extraction of the distributed cooling in a 4 K pulse tube cryocooler. 1. phase shifters; 2. hot heat exchanger of the 2nd stage; 3. warm temperature portion of the 2nd stage pulse tube; 4. 1st stage cooling station; 5. low temperature portion of the 2nd stage pulse tube; 6. 2nd stage cooling station; 7. 2nd stage regenerator; 8. 1st stage regenerator; 9. 1st stage pulse tube; 10. hot heat exchanger of the 1st stage; 11. rotary valve; a. manganin wire heater; b. temperature sensor; c. heater; d. manganin wire heater e. temperature sensor; f. heater.

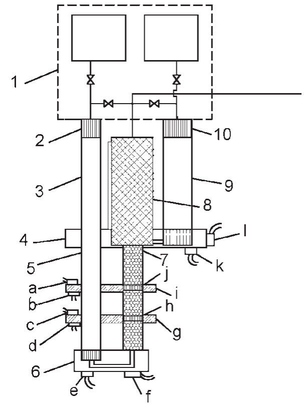

Figure 2. Schematic for extraction of the intermediate cooling in a 4 K pulse tube cryocooler. 1. phase shifters; 2. hot heat exchanger of the 2nd stage; 3. warm temperature portion of the 2nd stage pulse tube; 4.1st stage cooling station; 5. low temperature portion of the 2nd stage pulse tube; 6. 2nd stage cooling station; 7. 2nd stage regenerator; 8. 1st stage regenerator; 9. 1st stage pulse tube; 10. hot heat exchanger of the 1st stage; a. heater; b. temperature sensor; c. heater; d. temperature sensor; e. temperature sensor; f. heater; g. 2nd intermediate heat exchanger (HE2); h. heat exchanger inside of the regenerator; i. 1st intermediate heat exchanger (HE1); j. heat exchanger inside of the regenerator; k. temperature sensor; l. heater.

and (j) are inserted inside of the 2nd stage regenerator. These internal heat exchangers have good thermal contact with the intermediate heat exchanger HE1 and HE2.

Four calibrated silicon diode temperature sensors (b), (d), (e) and (k) as well as four resistive heaters (a), (c), (f) and (l) are mounted on the intermediate heat exchangers HE1 and HE2, the 1st and 2nd stage cooling stations.

The distributed cooling is first measured on the standard PT410, as shown in Figure 1. After the measurement, the PT410 was then modified by installing the intermediate heat exchangers HE1 and HE2. The cooling performance of the PT410 is different slightly after the modification. During all tests, a continued heat load of 1.0 W was applied to the 2nd stage of the PT410.

EXPERIMENTAL RESULTS AND ANALYSIS

Distributed Cooling

Figure 3 shows the effects of distributed cooling from the 2nd stage pulse tube on the 1st and 2nd stage performance. During the test, the 1st stage has no heat load and the 2nd stage has a heat

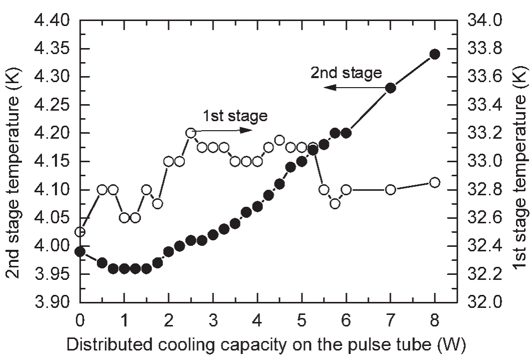

Figure 3. Effects of distributed cooling from the pulse tube with no load on the first stage

load of 1 W. The temperature on the first stage is 32.5 K and that on the 2nd stage 3.99 K. Extracting cooling capacity of < 2 W from the pulse tube increases the 2nd stage performance to some degree. Extracting cooling capacity of > 2 W slowly reduces the 2nd stage performance. The 2nd stage pulse tube can provide the distributed cooling of 6 W and still keep the 2nd stage cooling station at 4.2 K with 1 W heat load. The first stage temperature oscillates between 32.5 K to 33.2 K when applying the distributed heat load of 0 to 8 W to the 2nd stage pulse tube.

Figure 4 shows the effects of distributed cooling from the 2nd stage pulse tube while the first stage maintains at 45 K. When the distributed heat load on the pulse tube is less than 2 W, there is no change on the 2nd stage temperature. It starts to increase when the heat load is higher than 2 W. The 1st stage cooling capacity decreases when extracting cooling from the pulse tube. The cooling capacity of the 1st stage at 45 K decreases from 52.5 W to 50 W during extractive cooling of 0 to 7 W from the pulse tube.

Figure 5 shows the effects of distributed cooling from the 2nd stage regenerator while there is no heat load on the first stage. Extracting the cooling from the 2nd stage regenerator slowly decreases the performance of the 1st and 2nd stage. The 2nd stage temperature increases from 3.99 K to 4.31 K during the extraction of 0 to 3 W from the regenerator.

Figure 6 shows the effects of distributed cooling from the 2nd stage regenerator while the first stage is maintained at 45 K. The extraction of cooling has a larger impact on the first stage cooling capacity when the first stage temperature is at a higher temperature. It can be seen when comparing Figure 5 and Figure 6. The first stage cooling capacity drops by 9.9 W when applying a distributed heat load of 2.2 W on the regenerator.

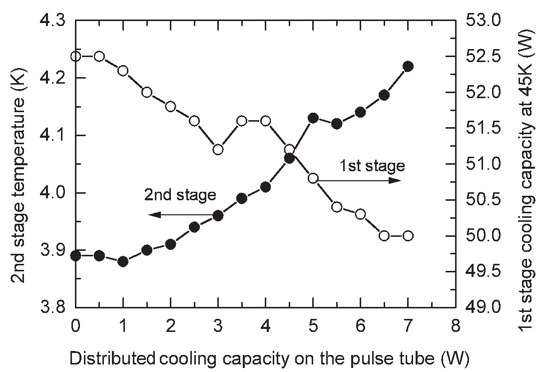

Figure 4. Effects of distributed cooling from the pulse tube with the first stage at 45 K.

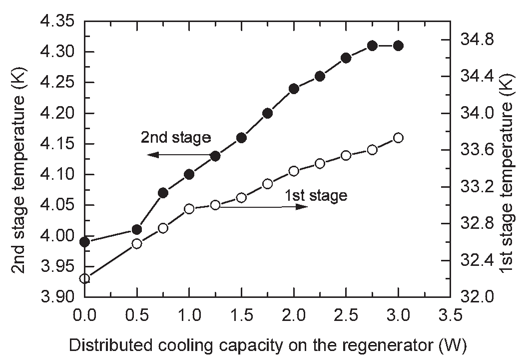

Figure 5. Effects of distributed cooling from the regenerator with no load on the 1st stage.

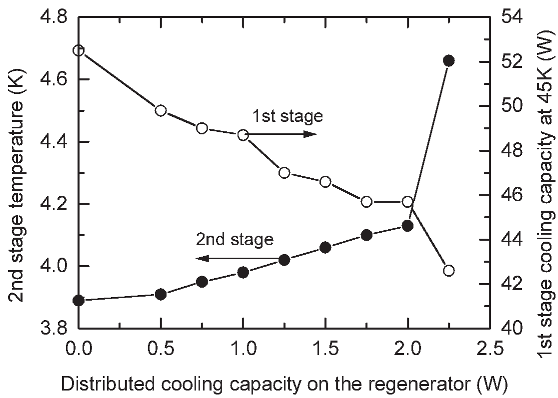

Figure 6. Effects of distributed cooling from the regenerator with the first stage at 45 K.

Capacities of distributed cooling from the 2nd stage pulse tube and regenerator are compared in Figure 7. The 2nd stage pulse tube provides much higher capacity of distributed cooling than the 2nd stage regenerator. The pulse tube can provide a capacity of 6 W and the regenerator only 2-3 W when maintaining the 2nd stage temperature below 4.2 K. So far, there is no complete explanation for this. A numerical analysis will be performed to understand its working process and find out the answer. We can also see from the comparison that lower 1st stage temperature leads to a higher capacity of distributed cooling.

Intermediate Cooling

The intermediate cooling on the heat exchanger HE1 and HE2 are measured separately. Figure 8 shows the intermediate cooling capacity from the HE1 while there is no heat load on the first stage. When applying 2 W heat load to the HE1 at 14.3 K, there is no effect on the 2nd stage temperature. But it increases the first stage temperature from 31.2 to 32.1 K. The HE1 can provide 5 W at 25 K while the 2nd stage is at 4.09 K with 1 W heat load.

Figure 9 shows the intermediate cooling capacity from the HE1 when the first stage is at 45 K. The HE1 can provide 3.5 W at 26 K without affecting the 2nd stage performance. However, the 1st stage cooling capacity drops from 58 W to 50.6 W at 45 K. It causes high degradation of the first stage performance.

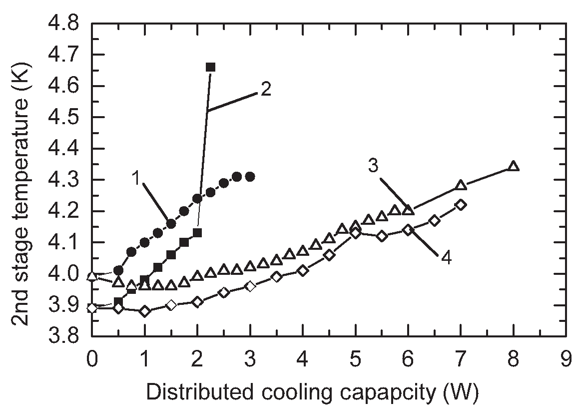

Figure 7. Capacity comparison of distributed cooling from the pulse tube and regenerator. 1. from the regenerator with no load on the 1st stage; 2. from the regenerator with the 1st stage at 45 K; 3. from the 2nd stage pulse tube with no load on the first stage; 4. from the 2nd stage pulse tube with the 1st stage at 45 K.

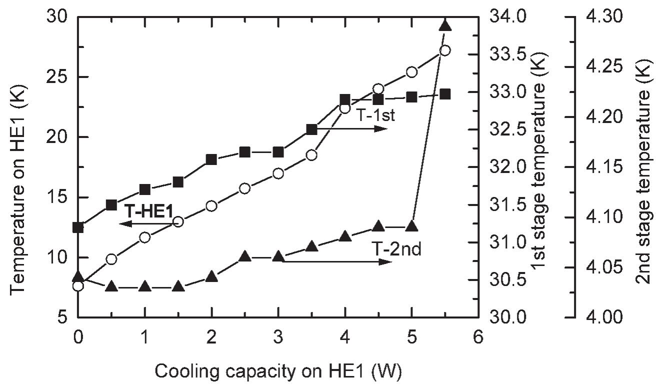

Figure 8. Intermediate cooling from HE1 with the first stage at the bottom temperature.

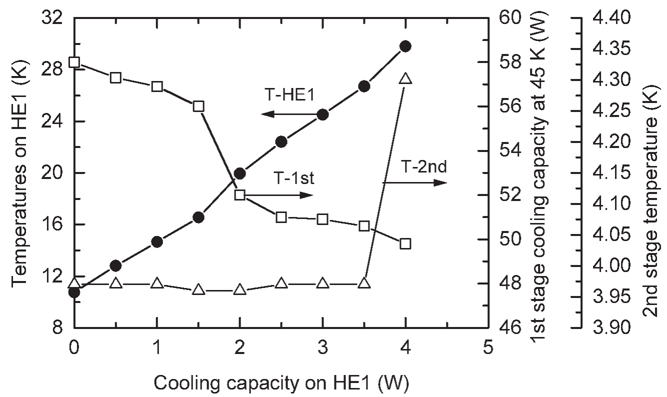

Figure 9. Intermediate cooling from HE1 with the first stage at 45 K.

Figure 10 shows the intermediate cooling capacity on the HE2 with the first stage at the bottom temperatures. It can only provide 0.5 W at 6.5 K while maintaining the same 2nd stage performance. When increasing the heat load on the HE2 to 0.75 W, the 2nd stage temperature jumps to 4.5 K.

Figure 11 shows the intermediate cooling capacity on the HE2 when maintaining the 1st stage at 45 K. It provides a similar cooling capacity with the first stage at the lower temperatures. Extracting cooling on the HE2 also results in large degradation on the first stage performance.

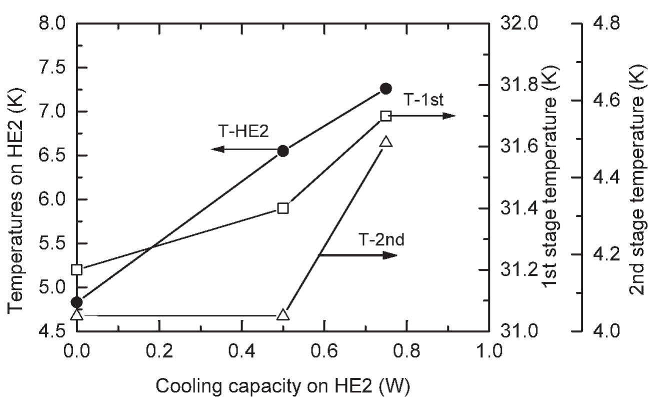

Figure 10. Intermediate cooling from HE2 with the first stage at the bottom temperature.

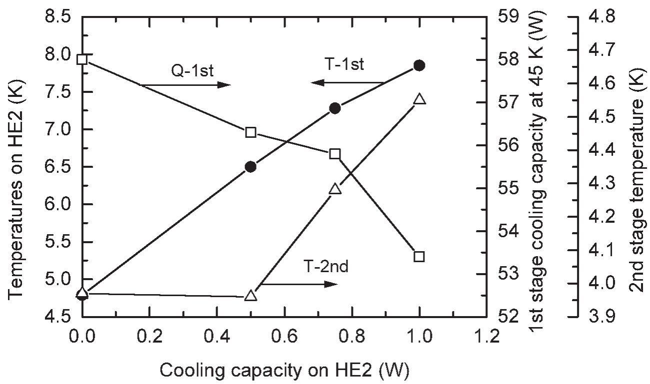

Figure 11. Intermediate cooling on the HE2 with the first stage at 45 K

Capacities of the intermediate cooling on the HE1 and HE2 are compared in Figure 12. The intermediate heat exchanger located towards the warm end can provide higher cooling capacity at higher temperatures. The location of the intermediate heat exchanger can be selected to provide the desired capacity and temperature of intermediate cooling.

CONCLUSION

Excess cooling can be extracted from both the 2nd stage pulse tube and regenerator in a two-stage pulse tube cryocooler. The 2nd pulse tube provides a much higher capacity of distributed cooling than the 2nd stage regenerator with less effect on the cooling performances of both stages. The joint intermediate heat exchangers on the pulse tube and regenerator have been demonstrated that a cooling capacity of up 3.5 W can be extracted without an effect on the 2nd stage performance. Extracting cooling from the pulse tube and regenerator results in degradation of the first stage performance.

A numerical simulation will be performed in the future to analyze the working process of the extracting cooling from the pulse tube and regenerator. It will explain how the pulse tube provides the excess cooling and how extracting cooling affects the first stage performance.

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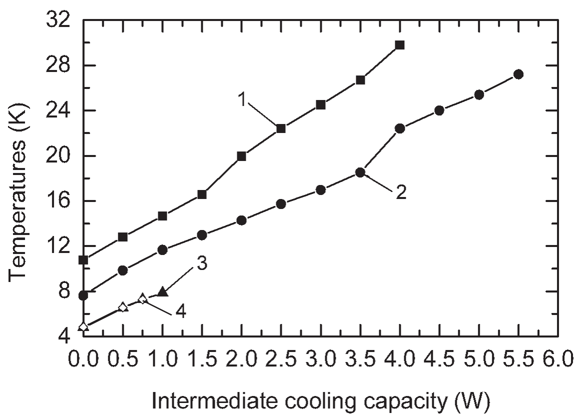

Figure 12. Comparison of intermediate cooling capacities from the HE1 and HE2. 1. from the HE1 with the 1st stage at 45K; 2. from the HE1 with no load on the 1st stage; 3. from the HE2 with the first stage at 45K; 4. from the HE2 with no load on the 1st stage.

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