A Closed Cycle 1K Refrigerator Precooled by a 4K Pulse Tube Cryocooler

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ABSTRACT

We have developed a closed cycle 1 K refrigerator with features of continuous operation, low vibration and high reliability. The 1 K refrigerator is precooled by a 4 K pulse tube cryocooler, which provides ~0.5 W at 4.2 K with a power input of 4.6 kW. A vacuum pump with peak pumping speed of 35m^3/h was used to circulate helium from the 1 K pot to the liquefaction loop attached to the 4 K pulse tube cryocooler. The discharged helium gas is fed into the liquefaction loop to be precooled and condensed into liquid. An adjustable Joule-Thomson (JT) valve between the condenser and 1 K pot provides flexibility to obtain either the minimum temperature or the maximum cooling capacity on the 1 K cooling station. It can reach a minimum temperature of ~1.4 K and provide 200 mW of cooling at 1.65 K. The system design, optimization and performance is presented in this paper.

INTRODUCTION

Many applications, such as high field magnets, dilution refrigerators, detectors and cryostats for low temperature physics, require cooling below 2 K. Most of these applications utilize an open 1 K refrigeration system by pumping liquid helium through a Joule-Thomson (JT) valve. The pumped helium vapor is exhausted to the atmosphere and eventually the cryostat must be refilled with costly liquid helium. Often helium is pumped to a recovery system which conserves helium for reuse but adds increased cost and space constraints.

Two dry 1 K refrigeration systems [1,2], precooled by 4 K pulse tube cryocoolers, had been developed by using a helium gas cylinder to supply helium gas to 1 K refrigeration loop. Liquid helium usage is eliminated, but the 1 K systems are an open loop and the pumped gas exhausted to the atmosphere. F.M. Piegsa, et al., presented a high power closed-cycle ^{4}He cryostat with top-loading sample [3]. It consists of two Roots pumps in series, with nominal pumping speeds of 1000 m^3/h and 300 m^3/h, backed by a 35 m^3/h scroll pump. A base temperature of 1.0 K is reached and a cooling power of 250 mW is established at 1.24 K. Closed-cycle 1 K refrigeration loops precooled by a 4 K PT cryocooler have been integrated into dry dilution refrigerators [4,5], but are not available commercially as a standalone option. All above works are using a capillary tube as the JT impedance.

An ultra-low vibration closed-cycle cryostat had been developed at Cryomech, Inc. [6]. The cryostat used a sleeve to prevent mechanical contact between the PT cryocooler heat exchangers and the 1 K cooling station resulting in almost no vibration transfer to the instrumentation cooling

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station. The drawbacks of this system are (1) it has a larger size and (2) it cannot provide efficient cooling for the 1st stage at ~45 K.

We developed a commercial, compact closed-cycle 1 K cryocooler which can simultaneously provide high cooling capacities at temperatures of ~45 K, ~ 4 K and ≤ 1.8 K. The design, performance optimization and application utilizing piezoelectric-based nanopositioners are described in this work.

1K CRYOCOOLER DESIGN AND INSTRUMENTATION

Figure 1 shows a schematic of the 1 K cryocooler precooled by a 4 K pulse tube cryocooler. A digital rendering of the 1 K cryocooler cold head and a photo of the pumping station are given in Figure 2. The 4 K pulse tube cryocooler is a Cryomech model PT405-RM, which can provide 0.5 W at 4.2 K. In the 1 K circulation loop, the inlet helium gas at an absolute pressure of ~115 kPa is precooled by a heat exchanger (15) on the 1st cooling station (3) and a heat exchanger (14) on the 2nd stage regenerator and is then condensed in a condenser (6) on the 2nd stage (5). The heat exchanger (14) wrapped around the 2nd stage regenerator is a stainless-steel tube with an ID of 4.5mm. The relatively large diameter tube is used to reduce the chance of impurity blockage during the operation as there is no actively cooled getter material in the 1 K loop. Precooling helium gas with the 2nd stage regenerator for efficient helium liquefaction was analyzed in [7]. The condenser, thermally anchored on the 2nd stage of the cold head, is made of a small copper tube. The condensed helium flows through a counter-flow heat exchanger (11) to be cooled to ~ 2 K. It then passes through a JT valve (12) and reduces its pressure in a 1 K pot (10).

The 1 K pot is pumped by a dry vacuum pump (1) through a pumping line (4). Three different dry pumps were tested with peak pumping speeds of 11.4, 15.1 and 35 m³/hr. A reservoir (16) is installed at the pump discharge side to stabilize the pressure. The vacuum pump and reservoir volume are installed in a pumping station with in and out Aeroquip connectors on the front. Both inlet and outlet helium gas ports on the 1 K cold head also have Aeroquip connectors for connecting the discharge side and suction side of the pump. Both suction side connecting line and discharge

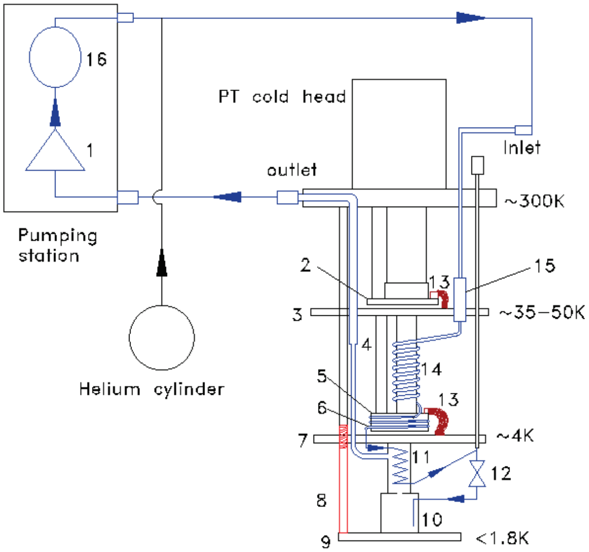

Figure 1. Schematics of the closed-cycle 1 K cryocooler. 1. Dry vacuum pump; 2. 1st stage; 3. 1st cooling station; 4. Pumping line; 5. 2nd stage; 6. condenser; 7. 4 K cooling station; 8. Thermal switch; 9. 1 K cooling station; 10. 1 K pot; 11. Counter flow heat exchanger; 12. Needle valve; 13. Flexible thermal bridge; 14. Heat exchanger; 15. Heat exchanger; 16. Gas reservoir.

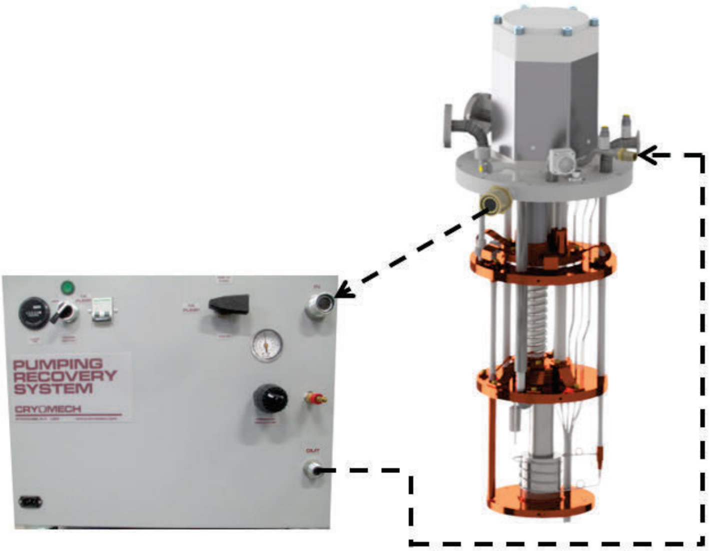

Figure 2. Photo of the pumping station and digital rendering of the 1 K cryocooler

side line are stainless steel flexible lines. A standard helium gas cylinder is connected to the discharge side of the pump for adding helium if needed. The Aeroquip connectors seal helium gas in each component of the 1 K loop after disconnecting them and can eliminate contamination during assembly.

The 1 K pot needs to be thermally isolated from the rest of the system but this significantly effects the cool-down speed. A mechanical thermal switch (8) consisting of a copper rod that is threaded at one end is installed between the 4 K cooling station and 1 K station to reduce cool-down time of the system. The switch is manually activated by rotating a knob on the room temperature flange. The 1st cooling station (3) and 4 K cooling station (7) are thermally connected with the cold head 1st stage (2) and 2nd stage (5) through the flexible thermal bridges (13) made of OFHC copper ribbon. The flexible thermal connections reduce the vibration transferred to the cooling stations from the PT cold head. The three cooling stations of (3, 7 and 9) can provide cooling power at temperatures of ~45 K, ~4 K and <1.8 K simultaneously.

In the testing rig, two aluminum radiation shields are thermally anchored on the 1st cooling station and the 4 K cooling station. Three calibrated silicon diode temperature sensors are mounted on the 2nd stage condenser, 4 K cooling station and 1st cooling station, which have calibrated accuracies of ±12 mK. A calibrated Cernox RTD (Lakeshore model CX-1030-CU-1.4L) is installed on the 1 K cooling station, which has a calibrated accuracy of ±5 mK. A heater is installed on the 2nd stage to maintain constant vapor pressure in the condenser loop. Another heater is installed on the 1 K cooling station to measure its cooling capacity. Heater power measurements are made using 4 leads to measure the voltage and current across the 1 K cooling station heater. Flow rate in the 1 K loop is measured using a flow meter made by Teledyne Hastings Instruments (model HFM-200) with a range of 0 – 20 SLPM and an accuracy of 0.2 SLPM.

EXPERIMENTAL RESULTS AND DISCUSSION

Performance

The cooling capacity of the PT405-RM was measured prior to integration into the 1 K loop, which is shown in Figure 3. The cryocooler can provide 0.45 W at 4.1 K with the 1st stage at 40 K and 0.52 W at 4.2 K while the 1st stage has 22 W at 65 K.

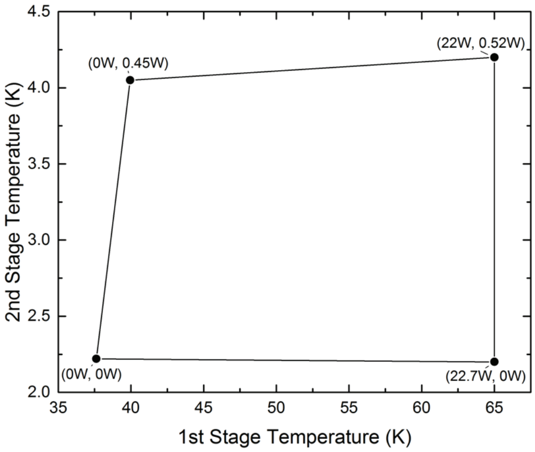

Figure 3. Cooling load map measured with the PT405-RM pulse tube cryocooler

The cool-down performance was measured with the thermal switch engaged and disengaged. The 1 K cooling station reached 5 K in 19.4 hours with the switch disengaged and 9.0 hours with the switch engaged, as shown in Figure 4. The addition of the thermal switch reduced the cool-down time by a factor of 2.15. Although the cool-down performance improved significantly, Figure 5 shows that the 1 K cooling station does not reach as low a base temperature with the switch engaged. It also takes a longer time to stabilize. This is due to poor thermal contact between the thermal switch and 4 K cooling station leading to higher conduction losses to the 1 K cooling station. This will be improved in future designs. Unlike previous 1 K cryocoolers with a liquid reservoir [6], the dry vacuum pump can be activated immediately after reaching base temperature as there is no need to fill a liquid reservoir with helium. The 1 K stage cools to below 1.8 K in ~5 minutes after turning on the vacuum pump.

The 1 K cryocooler was tested with three different dry vacuum pumps which have peak pumping speeds of 11.4 m^3/hr, 15.1 m^3/hr and 35 m^3/hr. Figure 4 shows the temperature of the 1 K cooling station with a 100 mW heat load for each peak pumping speed. Each test used a 40° valve opening. As expected, the temperature decreases with increasing peak pumping speed. The heat load applied

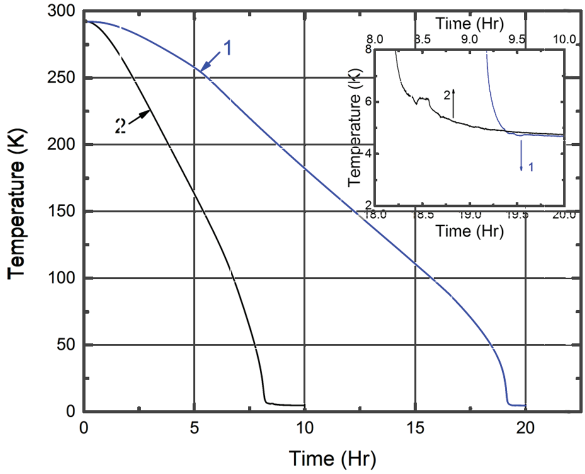

Figure 4. Cool-down curves for the with 1. Thermal switch disengaged and 2. Thermal switch engaged

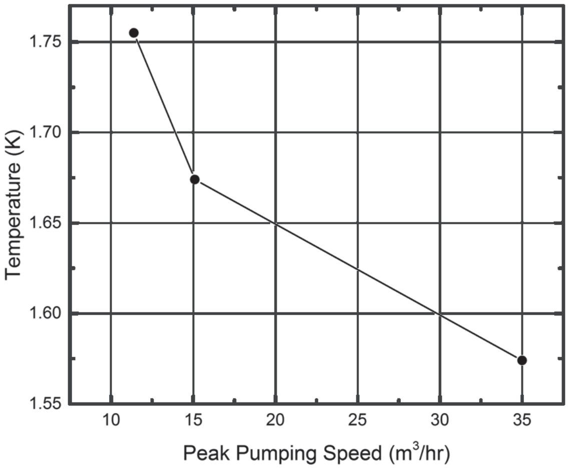

Figure 5. 1 K station temperature with 100 mW for three dry vacuum pumps with peak pumping speeds of 11.4 m3/hr, 15.1 m3/hr and 35 m3/hr

generates a constant boil-off of superfluid helium in the 1 K pot. As pumping speed increases, the flow rate increases as well and the vapor pressure in the 1 K pot decreases. All subsequent results reported in this work are with the 35 m^3/hr vacuum pump.

Using a needle valve as the JT impedance serves two purposes: to vary the cooling capabilities of the 1 K cooling station between low temperature and high capacity and allow for adjustment of the JT orifice should a blockage ever occur in the 1 K loop. Smaller valve openings allow for a lower base temperature but also a lower critical capacity, Qc. Beyond the critical capacity, all liquid helium in the pot boils off and the temperature rapidly increases. The low temperature and high capacity performance of the 1 K station is shown in Figure 6. The cryocooler achieves a minimum base temperature of 1.42 K in the low temperature setting and a maximum cooling capacity of 200 mW at 1.65 K in the high capacity setting. In the low temperature settings, cooling is also generated on the 4 K stage at 4.2 K. The high flow rates in the 1 K loop obtained in the high capacity setting places an increased heat load on the 2nd stage, leading to higher temperatures.

There is direct thermal contact between the 1st and 2nd stages of the pulse tube cold head to the 1st cooling station and 4 K cooling station, respectively. This allows for cooling on all three stages of the cryocooler, simultaneously. The temperature of the 2nd stage and 1st cooling station were mea-

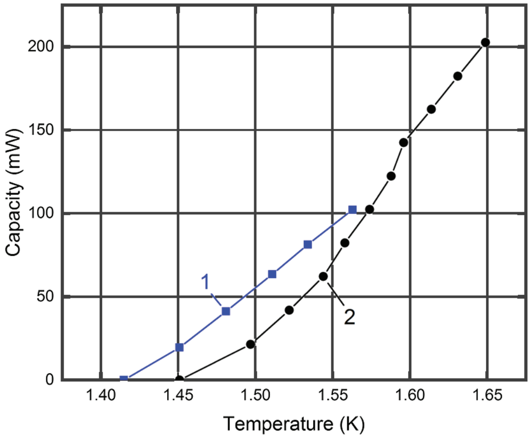

Figure 6. Cooling Capacity curves for a 1. 30° valve opening and 2. 40° valve opening

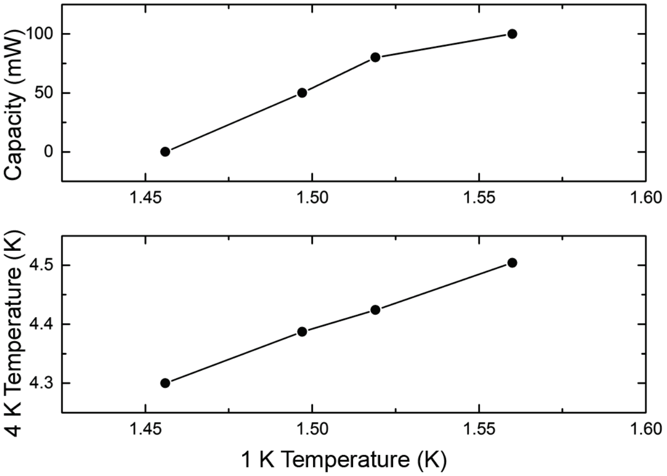

Figure 7. Cooling capacity and 2nd stage temperature vs. 1 K cooling station temperature

sured at various 1 K temperatures. Figure 7 shows the temperature on the 1 K cooling station and 2nd stage. The temperature of the 2nd stage increases with increasing 1 K cooling station temperature. This is due to increasing vapor pressure in the 1 K pot which causes higher flow rates through the 1 K loop. The temperature of the 1st cooling station was measured to be a constant 49 K due to the relatively small changes in flow rate compared to the large capacity on the 1st stage. As discussed in the previous section, the critical cooling capacity decreases with decreasing valve opening due to the boil-off rate in the 1 K pot being larger than the flow rate into the pot. It was found that the critical cooling capacity decreases for increasing valve openings as well. If the flow rate is too high, the heat load on the 2nd stage will be too large to liquefy helium and the 1 K pot will dry out.

The temperature stability was measured for cases of a constant applied heat load and using a PID temperature controller to maintain a constant temperature. In each case, the 1 K cooling station maintained sub-millikelvin temperature stability over time periods of 1 hour. Over a few hours, the temperature in the case of constant heat load drifted by 5 mK. This temperature drift is due to changes in ambient temperature. Figure 8 shows the temperature stability with a constant heat load of 100 mW for 3 hours and PID controlled for ~60 hours to 1.55 K. The resolution of the temperature monitor used in this study is 1 mK. The PID controlled stability appears constant at this resolution so the temperature fluctuation must be in the sub-millikelvin range. Future work will measure the temperature stability in similar systems with a higher resolution device.

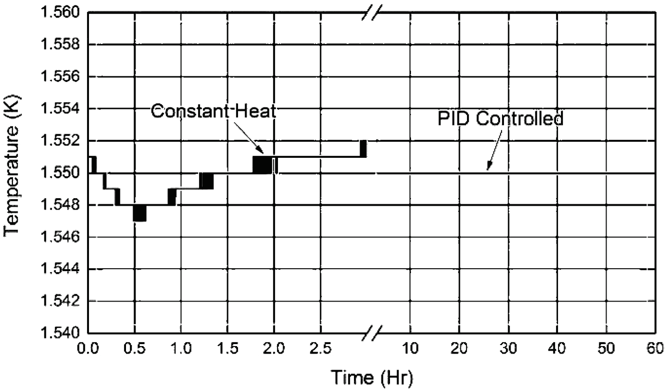

Figure 8. Temperature stability with a constant 100mW heat load and PID controlled for 60 hours

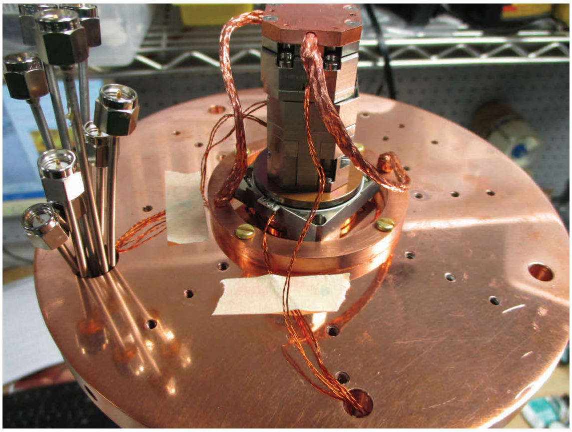

Figure 9. Nanopositioner stack with sample mount and flexible thermal connections

APPLICATION

The system was integrated with a piezo-based nanopositioner stack made by Attocube for nanometer-scale position adjustment. The stack consists of four nanopositioners to provide motion in the x, y, z and rotational axes. A sample mount made with flexible thermal connections was specially designed to thermally link the users sample with the 1 K cooling Station. Figure 9 shows a photo of the nanopositioner stack with sample mount connected to the 1 K cooling station. The flexible thermal link was designed be long and flexible enough to allow a full 5 mm movement in three axes and ~90° rotation while still providing efficient heat transfer.

A Ruthenium Oxide RTD was mounted to the sample mount to measure the cool-down performance and base temperature with the nanopositioners connected to the system. Figure 10 shows the cool-down curve and base temperature on the 1 K cooling station and sample mount. The 1 K cooling station and sample mount cooled to below 5 K in 10 hours with the thermal switch engaged. The cool-down time increased by 1 hour due to the additional heat load from the nanopositioner wiring. The dry pump was then turned on and the base temperature was measured to be 1.60 K on the 1 K cooling station with a very small 12 mK temperature difference across the thermal link with a 70° valve opening. Closing the valve to 40° caused the 1 K cooling station and sample mount

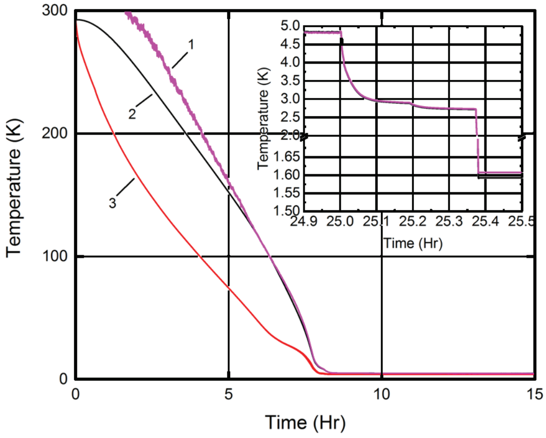

Figure 10. Cool-down performance with nanopositioners installed measured on the (1) sample mount, (2) 1 K cooling station and (3) 2nd stage

temperatures to decrease to 1.41 K and 1.43 K respectively. The 1 K cryocooler with integrated nanopositioners will be used in single photon detection experiments.

CONCLUSION

A closed-cycle 1 K cryocooler, precooled by a pulse tube cryocooler, has been developed to provide cooling at ~50 K, ~4 K, and <1.8 K with fast cool-down speed and sub-millikelvin temperature stability. The system provides 200 mW of cooling at 1.65 K and a base temperature of 1.41 K. The system was integrated with piezo-based nanopositioners for ultra-fine sample positioning and will be used in single photon detection experiments. It has become a commercially available 1 K cryocooler for research laboratories.

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