1 K cryostat with sub-millikelvin stability based on a pulse-tube cryocooler

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Abstract

A cryogenic system has been designed and tested that reaches a temperature below 1.1 K, with an rms temperature stability of 25 μ K. In this system a commercial pulse-tube cryocooler is used to liquify helium gas supplied from an external source. This liquid helium enters a 1 K pot through a large-impedance capillary tube, similar to a conventional 1 K system operated from a liquid helium bath. Unlike a conventional system, however, the molar flow rate of the system can be varied by changing the pressure of the incoming helium. This allows for a trade-off between helium usage and cooling power, which has a maximum value of 27 mW. The measured cooling power and fraction of helium exiting the capillary as liquid agree well with predictions based on an isenthalpic model of helium flow through the capillary. The system is simple to use and inexpensive to operate: The system can be cooled to base temperature in about 3 hours and, with a flow rate giving a cooling power of 13 mW, the helium cost is around \$6 per day.

Keywords: 1 K Pot, Pulse-tube cryocooler, Helium liquefaction, Heat exchanger, Joule-Thompson impedance

1. Introduction

Research at cryogenic temperatures has been fundamentally transformed by the recent development of closed-cycle cryocoolers featuring reliable, cryogen-free operation and capable of reaching temperatures below 4 K. In an era of helium scarcity and increasing liquid helium prices, closed-cycle cryocoolers are a particularly attractive means of reaching liquid helium temperatures in a highly cost-effective manner.

Closed-cycle cryocoolers have some disadvantages compared with traditional liquid-helium systems. First, the cyclic nature of a pulse-tube cryocooler leads to rather large temperature oscillations, on the order of 0.2 K, at the ~ 1 Hz frequency of the cooler's operation [1]. Second, while base temperatures have continued to improve over the years, they are still above the ~ 1 K temperature reachable with pumped helium systems.

One way to overcome these disadvantages is to use the 4 K stage of the closed-cycle cryocooler to liquefy helium gas from an external source. The liquid helium is then further cooled as it is pumped through a Joule-Thompson impedance, filling a reservoir, or pot, at a temperature near 1 K. The temperature of the helium in the pot is much more stable than that of the cryocooler's 4 K cold head.

Several recent papers have described hybrid cryogenic systems using this scheme. In a system built by Wang and co-workers [2], helium is first liquefied by the cryocooler's cold head into a large reservoir holding ~ 1 L of liquid helium at 4 K. Helium from this reservoir is then pumped through a Joule-Thompson valve into the 1 K pot. This system provides a large

cooling power (100 mW at 1.74 K) at the expense of high helium usage and a long (~ 30 h) cooldown time. The temperature stability at the 1 K stage was 24 mK peak-to-peak.

Jahromi et al. [3] have designed a system that reaches a base temperature of 1.4 K and has a large cooling power of 200 mW at 1.7 K. Although the authors give a wealth of information on the design and construction of their system, very little data on its performance is presented. In particular, no information on its cooldown time or temperature stability is given.

In this paper we describe a cryogenic system based on the idea of liquefying helium into a small pot and pumping it to 1 K. In our design we have paid particular attention to a number of issues that are important for researchers performing typical low-temperature physics experiments, such as transport measurements. First, the system is relatively easy to construct. We have designed it to be compact in size and have a minimum number of complex parts to fabricate. Second, its base temperature is quite low; we reach 1.10 K under single-shot conditions. Third, its temperature stability is excellent, with fluctuations of only 25 μ K rms (90 μ K peak-to-peak) observed with a full pot. Fourth, we have designed a modular wiring and sample loading system that allows samples to be very easily exchanged. Fifth, the system cools quickly (in about 3 h) to base temperature. And finally, our system has been designed to minimize the use of external helium, costing only a few dollars' worth of helium per day to run.

2. Cryocooler Design and Construction

2.1. Helium flow path and design details

The pulse-tube cryocooler used is a Cryomech PT403 with a cooling power of 0.25 W at 4.2 K and a measured base temperature of 2.8 K. A schematic of the helium flow through our

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system is shown in Fig. 1a. High-purity (UHP, or 99.999%) helium is provided by a standard compressed gas cylinder (A, Fig. 1a). The helium first passes through a mass flow controller B (Alicat MC series, 2 SLPM maximum flow) that can be set to control either the helium mass flow or pressure. After the helium line enters the cryostat vacuum chamber, the helium is precooled as it passes through heat exchanger C mounted on the 50 K first stage of the cryocooler. The heat exchanger consists of a sealed copper cylinder packed with fine copper mesh. This heat exchanger also acts as a cold trap, freezing out any residual impurities in the gas.

The helium next moves through heat exchanger D that is coupled to the cryocooler's second-stage regenerator tube. Efficiently precooling the helium as it cools from 50 K to 4 K is critical for efficient liquefaction of the helium [4, 5, 6, 7]. At 1 bar, the enthalpy change in helium as it cools from 50 K to 4 K is about 970 J/mol. At a typical operating flow rate of 0.5 mmol/s, cooling the helium directly at the second (4 K) stage would require a cooling power of about 0.5 W, far too high for our cryocooler. By allowing heat exchange between the incoming helium and the regenerator, which is pumping heat from the second stage to the first, about 90% of the enthalpy can be removed before reaching the second stage [4], leading to a much more reasonable ~ 50 mW second-stage heat load.

The heat exchanger must make good thermal contact with the regenerator tube. As Fig. 1a shows, this thermal contact is made using five copper thermal anchors between the (coiled) helium line and the regenerator tube [6]. Figure 2 shows a rendering of one of the thermal anchors and a section of the helium line; the entire heat exchanger is also visible in Fig. 1b. In Fig. 2, the copper frame and cylinder are silver soldered together. Each anchor is clamped to the regenerator tube using the thin stainless steel band shown. Two 2-56 screws tighten into matching hex nuts that are silver soldered to the band. The helium line consists of a 2.4 mm diameter, 0.25 mm wall (2.4 $\times$ 0.25) annealed stainless steel tube wound into a spiral with an outside diameter of 1.7 cm. To assemble the entire heat exchanger, each of the five anchors was clamped, using its band, to a heavy rod of the same diameter as the regenerator tube. The coiled helium line was then inserted through the copper tubes of each anchor and soft soldered into place. The assembled heat exchanger is gently tightened onto the regenerator tube using a thin layer of Apiezon N grease.

As will be shown in Sec. 3.5, the helium exits the regenerator heat exchanger at a temperature in the range of 5 to 13 K, depending on the helium flow rate. It liquefies as it flows through the condenser E, which consists of five turns of 2.4 $\times$ 0.35 copper tubing soft soldered to a copper cylinder, 1.9 cm in diameter and 2.8 cm tall. This cylinder is soldered to the 4 K plate that is directly attached to the pulse-tube second stage with Apiezon grease. After liquefaction, the helium passes through a 90 cm-long, 0.25 $\times$ 0.127 stainless steel capillary tube F. This tube acts as a Joule-Thompson impedance, allowing ~ 1 bar pressure differences between the incoming helium and the pot with flow rates on order of a few times 10^{-4} mol/s. The helium then enters the copper pot G, of inner diameter of 2.38 cm and volume

14.1 cm³, which contains 0.51 mol of helium when full. The pot is pumped through a 6.35 $\times$ 0.127 stainless steel tube H, which widens to 12.7 mm above the second stage plate. This pumping line is thermally anchored via a flexible copper braid to the 50 K plate, leading to an estimated heat leak to the pot of 1.7 mW. If desired, this leak could be reduced to the μ W level by further anchoring the pumping line to the 4 K stage.

During operation, two radiation shields are in place. Each is made from 1.27 mm-thick 1100-series aluminum. One shield is anchored to the 4 K stage and the other to the 50 K stage. Each shield is wrapped in ten layers of NRC-2 superinsulation. The bypass valve, shown in Fig. 1a, is normally closed during operation of the cryocooler. It is useful for evacuating the helium line at room temperature via the pot pumping line; without this valve, part of system is nearly isolated on the other side of the capillary.

The pressures at the helium inlet and outlet are measured using vacuum gauges P1 and P2 (Honeywell HSC series). Thermometers are mounted at several points on the cryocooler (see Fig. 1). The temperature T_1 of the first stage is measured using a silicon diode thermometer, the second stage and pot temperatures T_2 and T_p with calibrated Cernox thermometers, and the regenerator temperature with a calibrated carbon-glass thermometer. The silicon diode is measured using a Lakeshore DTC-500 temperature controller; the other thermometers are measured using a Conductus LTC-20 bridge.

2.2. Helium level detector

We have designed a level detector to continuously measure the helium level in the pot. The detector is a capacitor made up of two concentric cylindrical electrodes. The capacitance changes as rising helium, with dielectric constant $\epsilon = 1.057$, fills the space between the electrodes [8, 9, 10].

The detector is shown in Fig. 3. A 1 V_{rms}, 5 kHz driving signal is applied to the outer electrode, which has an inner diameter of 6.12 mm. The displacement current injected into the inner electrode, with outer diameter 4.75 mm, leaves the cryostat via a coaxial cable and is balanced by a General Radio 1615A capacitance bridge. By using a guard-electrode geometry, our detector can make highly accurate measurements of the helium level. As Fig. 3 shows, the inner electrode is shorter than the outer electrode. The remaining length is taken up by two electrically isolated guard electrodes that are held at ground. Because the inner electrode is held at virtual ground by the bridge, the electric field from outer to inner electrodes is almost perfectly radial, making the effects of fringing fields negligible. Thus the effective length of the capacitor is very accurately that of the inner electrode, which is 2.936 cm.

As the pot begins to fill, the helium starts to fill the gap between the outer electrode and the lower guard electrode. During this phase there is no change in the capacitance measured between the outer and inner electrodes. However, just as the level passes the 0.013 mm gap between the inner and guard electrodes, the capacitance begins to rise. The capacitance continues to rise until the level reaches the upper gap, at which point the capacitance again becomes constant. These lower and upper plateaus thus define the capacitance change associated

Figure 1: (a) Schematic of the cryocooler design. The commercial PT403 pulse-tube cryocooler is shown as semi-transparent. Thermometers T_1 , T_2 , T_R , and T_P are shown as small black rectangles (b) A photograph of the cryocooler before wiring was installed. For scale, the vacuum flange is 25.4 cm in diameter.

Figure 2: A computer rendering of one of five thermal anchors used to attach the coiled helium line to the regenerator tube.

with a rise of precisely 2.936 cm, very accurately calibrating the detector. Reassuringly, we find that this calibration agrees with the theoretical prediction of the capacitance of concentric cylinders to better than 1%.

2.3. Heat switch

By design, the pot is thermally well-isolated from the rest of the cryostat. It is connected only to the second stage, by a thin-wall (6.35×0.25), 3.8 cm-long stainless steel support tube, and to the first stage by the pot pumping line. Because of this, it can take a very long time to cool the pot from room temperature, especially if significant experimental masses are connected to the pot. To expedite the cooling process we have designed a simple mechanical heat switch, shown in Fig. 4. During the cooldown phase, a copper disk is held tightly against the second stage by a spring. This spring has a spring constant of 9900 N/m, and

Figure 3: The helium level detector. An ac voltage is applied to the outer electrode and the capacitor current is read from the center, inner electrode. The two guard electrodes are grounded. The top and bottom plastic spacer rings are C-shaped to allow helium to fill the space between the tubes.

exerts a force of 60 N when compressed. Thermal contact between the copper disk and the second stage is enhanced by a 0.25 mm thick indium washer between them. Three parallel 8 cm-long flexible braids, each made up of 168 36-gauge copper wires, connect the disk to the pot. With the switch in this closed position there is then good thermal contact between the pot and the second stage, allowing heat to be efficiently removed from the pot.

Figure 4: The mechanical heat switch used to couple the second (4 K) stage to the pot during cooldown. The lifting arm is longer than shown; the actual mechanical advantage of the lifting arm is 9:1. The hatched areas have been cut away in the drawing for clarity.

Once the second stage and pot have cooled to around 5 K the heat switch is opened. This is done by lifting a 0.025 cm diameter stainless steel wire that runs directly to room temperature. (We estimate the heat leak along this wire to be about 1 mW.) As the figure shows, the wire pulls up on the end of a lifting arm, which in turn pulls up on a second lifting wire that is connected to the copper disk, separating the disk from the second stage. This breaks the thermal connection between the pot and the second stage.

The wire to room temperature is raised using a simple pulley system. The wire is wrapped around a 0.95 cm diameter pulley attached to a horizontal shaft. The shaft exits the top of the cryocooler through a quick-connect-type fitting, where it is attached to a knob. The friction from the quick connect is sufficient to hold the heat switch in the open position.

3. Performance

3.1. Cooldown performance

The temperatures of the pot, the first stage, and the second stage as the cryocooler is cooled from room temperature are shown in Fig. 5. Whether or not the heat switch is closed the first and second stages cool relatively quickly. But with the heat switch open, so that there is only weak coupling between the pot and the second stage, the pot cools extremely slowly. Even after 40 h (not shown), the pot temperature only reaches 65 K. With the heat switch closed, however, the pot reaches 5 K in about 3 h. Once this temperature is reached, helium flow and liquefaction can begin, after which base temperature is reached in just a few minutes.

The inset to Fig. 5 shows the pot and second stage temperatures in a 15-minute interval around the 3-h mark of the

cooldown. At time (a) in the figure we start helium flowing into the system, but without pumping yet. At (b) the valve to the pot pump is opened. There is an initial rise in the pot temperature as warm helium flows into it, but the helium then begins to liquefy in the condenser and the pot temperature drops rapidly to around 1.6 K. At (c) the heat switch is opened, isolating the pot from the second stage and the system cools to its base temperature.

Figure 5: The temperatures of the first stage, second stage, and pot as a function of time, taken during two separate cooldowns with the heat switch open and closed. The inset shows the pot and second stage temperatures when helium flow is started around the 3 h mark, with the heat switch closed. See text for explanation of the points a, b, and c.

When more thermal mass needs to be cooled, the cooldown takes longer. The sample stage discussed later in Sec. 4.2 adds 360 g of copper to the system, and extends the cooldown time to 4.8 h.

3.2. Cooling power

In a traditional liquid helium cryostat with a pumped pot [11] the helium enters from a liquid bath at atmospheric pressure. Because the impedance is fixed, the molar flow and thus the resulting cooling power are also fixed. In our system, however, the pressure of the incoming helium, and hence the helium flow through the impedance, can be varied over a wide range. Low helium flows can be used when cooling requirements are modest, and higher flows used when more cooling power is needed. To fully characterize the performance of our system, then, key parameters must be measured as a function of pressure (or, equivalently, molar flow rate).

One way to determine the cooling power is to measure the pot temperature as a function of the external power applied to the pot [11]. Figure 6 shows the results of such experiments for input helium pressures ranging from 0.2 to 2.4 bar absolute. For each run the power was initially set to a value large enough that the pot was emptied of any liquid. The power was then slowly decreased. As the figure shows, the pot temperature drops rapidly until a *critical power* P_c is reached. Below the critical power the temperature still falls as the power is lowered, but much more slowly.

Figure 6: The temperature of the pot as a function of external power applied to the pot for input helium pressures ranging from 0.2 to 2.4 bar absolute. The critical power (shown by an arrow for the 0.4 bar data) is found from the intersection of the two quasi-linear segments of each curve.

We can interpret these graphs in the following way [11]. At high external powers the cooling power of the liquid helium entering the pot is less than the external power. The liquid immediately evaporates as it hits the pot walls, so no liquid collects in the pot. As the external power is reduced, the pot temperature falls, but no helium can collect until the external power is reduced to P_c . At this point, the cooling power of the entering liquid just equals the external power. Below P_c helium begins to collect in the pot. Once the pot contains liquid, its temperature varies much more slowly with external power [11].

In Fig. 6 the curves are very noisy above P_c but quiet below P_c . This behavior occurs because the helium exiting the capillary is a complex mixture of gas and liquid phases [11, 12], and because the heat capacity of the copper pot is extremely low, about 2 mJ/K at 1.4 K. When only gas is entering the pot, the cooling power is negligible and the pot heats rapidly, at roughly 5 K/s at a power of 10 mW. However, when liquid is entering, its latent heat rapidly cools the pot. Fluctuations in the gas/liquid content of the helium entering the pot thus lead to large fluctuations in its temperature.

At the critical power, the pot begins to fill with liquid. Now the fluctuations in the pot temperature are suppressed by the extremely large specific heat of liquid helium relative to copper; at 1.4 K, this ratio is 730:1 on a volume basis. Because the temperature of the pot is only stable for $P < P_c$, we identify the cooling power of our system with the critical power P_c .

The minimum temperature is reached with the pot full, but with no helium flow. The lowest temperature reached under these “single-shot” conditions was 1.109 K. With no external heat load, the pot will contain at least some helium, and thus maintain a temperature near this base value, for some 6 h. This corresponds to an internal heat load on the pot of around 2 mW.

In Fig. 7a we plot the critical power, determined from the graphs in Fig. 6, as a function of the input molar flow rate and

pressure. As expected, the critical power first increases as the molar flow rate increases because at higher rates there is more latent heat to provide cooling. At a rate of about 0.6 mmol/s the critical power reaches a maximum of 27 mW. At higher flow rates the critical power starts to decrease.

Figure 7: (a) The measured (●) and calculated (—) critical powers. (b) The fraction of helium entering the pot as liquid, inferred from critical power measurements (●), measured directly by the rate at which the pot fills (Δ), and calculated from an isenthalpic model (—).

This dependence of the critical power on flow rate can be understood if we assume that no heat is exchanged with the helium as it flows through the capillary, so that enthalpy is conserved [13]. We assume that the initial enthalpy is that of pure liquid at the second stage (condenser) temperature T_2 and pressure P_2 , and that the final enthalpy is that of a mixture of liquid fraction f and gas fraction $1 - f$, both at the pot temperature T_p and corresponding saturation vapor pressure P_p . Conservation of enthalpy H then requires

$$H_2^\ell = fH_p^\ell + (1 - f)H_p^g$$

from which the liquid fraction is

$$f = \frac{H_2^\ell - H_p^g}{H_p^\ell - H_p^g}, \quad (1)$$

where the superscripts ℓ and g denote liquid and gas phase enthalpies, respectively. With the liquid fraction calculated from Eq. 1, the cooling power can be calculated as

$$P_c = fL\dot{n}, \quad (2)$$

where L is the latent heat per mole at T_p and $\dot{n}$ is the molar flow rate.

The cooling power predicted from the isenthalpic model, Eqs. 1 and 2, is plotted as the solid curve in Fig. 7a. This curve is not completely a “theoretical” prediction, because the enthalpies used in Eq. 1 are found from the experimentally determined values of T_2 , P_2 , and T_p . We see that the correspondence with the experimental data is overall quite good, lending support for the isenthalpic model of helium flow.

There is some disagreement at very low and very high flow rates. At low flow rates, the data appear to extrapolate such that $P_c = 0$ at some nonzero flow rate. As the upper scale in Fig. 7a indicates, low flow rates are associated with low input pressures. At pressures below about 0.3 bar, the temperature required to liquify helium is below the *average* temperature T_2 of the second stage at the corresponding flow rate, so it would not appear possible to liquify helium in the condenser at such low pressures. We note, however, that the second stage temperature oscillates strongly at the period of the cryocooler compressor, so that for at least part of one cycle the condenser temperature is presumably below the liquefaction temperature, leading to a finite but suppressed liquefaction rate and cooling power.

At high rates the critical power is also lower than predicted. It is possible that in this high-flow regime the condenser cannot fully liquify the fast-moving incoming helium, leading to a lower liquid fraction f . However, we are unable experimentally to test this supposition.

3.3. Liquid fraction

As we’ve seen, the cooling power is determined in part by the fraction f of the helium flowing into the pot as liquid. This fraction is of interest when a cryocooler is used for small-scale helium liquefaction [14, 15, 7, 6, 4, 5]. We can find this fraction in three ways, as shown in Fig. 7b. First, Eq. 2 can be solved for f in terms of the measured quantities P_c and $\dot{n}$, and the known latent heat L . The liquid fraction calculated this way is shown by the filled circles in Fig. 7b. We also plot f as calculated directly from Eq. 1 as the solid line in Fig. 7b. Finally, we can directly measure the molar rate at which helium collects in the pot by using the calibrated level detector described in Sec. 2.2. Then f is equal to the ratio between this molar collection rate and the input molar flow. The liquid fraction found by this method is shown by the triangles in Fig. 7b. All three methods agree quite well, except at low flow rates where, as discussed above, the pressure is too low for efficient liquefaction to occur.

3.4. Temperature Stability

The data in Fig. 6 showed large fluctuations in the pot temperature when the pot is empty, but much smaller fluctuations when the pot contains liquid. Figure 8 shows this in more detail. Figure 8a shows the fluctuations as a function of time with helium flowing into the heated pot but with the pot empty (so the external power is greater than the critical power). The fluctuations are very large, on order of 0.4 K, as the incoming helium switches between liquid and gas. In Fig. 8b we show the temperature with the pot half full and completely full. In both cases the temperature fluctuations are strongly suppressed, especially for the full-pot case for which the rms fluctuations are

only 25 μ K. The fluctuations in this case are actually quite regular, and so presumably are not related to the incoming helium flow. The origin of these small periodic temperature fluctuations is not clear; their period is not commensurate with that of the pulse-tube compressor.

Figure 8: (a) The time dependence of the pot temperature with the pot empty. (b) Pot temperature with the pot half full and completely full. The vertical full scale of this graph is 1 mK. The half-full data has been offset vertically downward by 50 mK. For both (a) and (b) the external power was 14 mW and the helium flow rate was 0.20 mmol/s.

3.5. Regenerator heat exchanger performance

As discussed in Sec. 2.1, for efficient helium liquefaction in the condenser it is critical to remove heat from the incoming 50 K gas using a heat exchanger coupled to the regenerator tube of the cryocooler. Wang [4] has performed a numerical analysis of this heat exchange process. He assumes the helium enters the regenerator heat exchanger at a temperature of 62 K and leaves it at a temperature $T_R = 6.2$ K. His analysis shows that the fraction α of the heat absorbed into the regenerator that ends up heating the second stage is 11%. We have measured this coefficient for our system and have found it to be generally higher than this value, especially at higher flows.

To analyze this process, we note that helium enters the regenerator heat exchanger at the first stage temperature T_1 and leaves it at the much lower temperature T_R . The enthalpy removed from the gas is then $H_1 - H_R$, where H is the molar enthalpy at the first stage (1) or regenerator output (R). A fraction α of this enthalpy change ends up heating the second stage; the remainder is pumped up the regenerator to the first stage. After leaving the regenerator heat exchanger the gas is then liquified in the condenser, ending up as liquid at the second stage temperature. During this process the enthalpy change is $H_R - H_2$, where H_2 is the enthalpy of liquid helium at the second stage temperature.

The power $\dot{Q}_2$ heating the second stage is then

$$\dot{Q}_2 = \dot{n} [\alpha (H_1 - H_R) + H_R - H_2] \quad (3)$$

where $\dot{n}$ is the molar flow rate. Solving this equation for α gives

$$\alpha = \frac{\dot{Q}_2 / \dot{n} - (H_R - H_2)}{H_1 - H_R} \quad (4)$$

Figure 9: (●) The fraction α of heat exchanged with the regenerator that enters the second stage, plotted versus molar flow. (○) The temperature T_R of the helium exiting the regenerator heat exchanger.

As a function of flow we have measured T_1 , T_2 , T_R , and the pressure P , from which the enthalpies H_1 , H_2 , and H_R can be calculated. $\dot{Q}_2$ is found by measuring T_2 as a function of electrical heating power at zero flow. From this data, we can infer $\dot{Q}_2$ under flow conditions by measuring T_2 . The resulting values for α calculated from Eq. 4 are plotted in Fig. 9, along with the regenerator temperature T_R . We see that for low flow rates ($\dot{n} \lesssim 0.4$ mmol/s), α is indeed in the range of 11–12%, as predicted by Wang [4]. However, at higher flow rates α begins to climb, reaching 24% at 0.75 mmol/s. These measured values may differ from those found by Wang because of the very different temperatures at the output of the regenerator: at high flows we measure $T_R \approx 13$ K, while Wang assumes a temperature of 6.2 K throughout his analysis.

4. Practical Considerations

4.1. Operation

In practice the cryocooler is straightforward to operate. Referring to Fig. 1a, at room temperature the helium system is pumped out up to the mass flow controller with the bypass valve open, using the pot pump, a Welch 500 L/min rotary vane pump. The vacuum can is pumped out using a small turbopump system and the heat switch is closed. After 10 minutes or so the pot isolation valve is closed and the cryocooler compressor is started. When the second stage temperature reaches 5 K or so, helium flow can begin. We close the bypass valve and start the mass flow controller. A pressure rise on gauge P2 shows that helium is flowing through the capillary. With the pot pump on, the pot isolation valve is opened and the pot cools rapidly,

reaching 1.2 K in a few minutes. We have had no issues with the capillary becoming blocked, even after many days of continuous helium flow.

4.2. Wiring and sample mounting

One disadvantage of any system with a pumped pot is that the temperature of the filled pot is relatively constant, independent of the heat load [11] (see Fig. 6). Thus the temperature range available with the pot full is rather limited. We have extended this range somewhat by using a sample stage that is only moderately thermally coupled to the pot. As shown in the fully-wired photo of Fig. 10a, six copper braids serve as thermal links between the pot and the fixed sample stage. In this configuration the stage's minimum temperature is 1.35 K, and it can be heated to 2.6 K without overloading the pot.

As is often the case with cryogenic systems, the cold end of the cryocooler is hanging from above and is awkward to access. We have thus designed our system so that samples and other objects to be cooled are easy to attach and remove from the sample stage. In Fig. 10a, the fixed sample stage is permanently attached (via thinwall stainless posts and the copper braids) to the pot. Samples themselves, however, are mounted on a separate, removable stage consisting of a hexagonal copper plate, as shown in Fig. 10b. Thus samples can be conveniently mounted at the workbench, under a microscope if needed. The removable stage is then screwed to the fixed stage (with a thin layer of Apiezon N grease) for cooldown. A key feature of this system is the three banks of 20 spring-loaded pins (Mill-Max 854/856 series) that make electrical contact between the fixed and removable stages. This avoids any soldering of wires, or attaching of connectors, when the sample stage is mounted. As Fig. 10b shows, we have constructed separate removable stages for mounting a cryogenic scanning Hall probe microscope, and for testing the probes at low temperatures.

The modularity of construction extends to the low-thermal-conductivity wiring from room temperature. The wiring consists of twisted pairs of either 32- or 36-gauge phosphor-bronze wire. Six or nine pairs are varnished together into flat ribbon cables. The wires at each end of these cables are soldered to a small circuit board that also contains either a 12- or 18-pin header (Samtec FTSH series). This header plugs into a mating socket (FLE series) on a circuit board ("heat sink" in Fig. 10a) attached to the fixed stage. If a short were to develop in a wiring harness, it could be easily removed for repair.

Thermally anchoring of the wires to the various stages is also modularized. The heat-sink circuit board in Fig. 10a receives the wiring from a warmer stage. The traces from the connector on the top side of the board go through the board and run along its bottom face before mating with the spring-pin connector. These bottom-side traces are heat sunk to the copper stage by a thin cigarette-paper spacer that is varnished to the circuit board and greased to the sample stage. This construction avoids trying to individually heat sink the 48 copper wires that reach the sample stage, and allows for easy removal of the board for repair.

Figure 10: (a) Pot and cold stages of the cryocooler. Low-thermal-conductivity wire harnesses plug into sockets on the green circuit boards, which also serve as heat sinks to the cold stage. The removable stage makes electrical contact with the fixed stage via 60 spring-loaded pins. (b) Three different removable stages, used (from left to right) for transport measurements, testing Hall probes, and mounting the Hall microscope.

4.3. Operating costs

Although the cryocooler uses an external source of helium, the amount of helium used is very small. Our standard UHP helium cylinders contain 342 mol of helium and cost \$112. At a molar flow of 0.2 mmol/s (giving a cooling power of 13 mW), this tank will last for 480 h, giving a helium cost of \$0.24/h. In practice, while the cryocooler is cold we are often not flowing helium so the tank lasts significantly longer than 480 h.

We can contrast this cost with that of running our previous liquid-helium based system. That system required 13 L of liquid helium for a 12 h run. Current liquid helium costs (with gas recovery) are in the range of \$8–\$9/L, so the running cost of the previous system was at least \$10/h. The effective cost was probably double that, because of inefficiencies in helium storage and transfer, and, in particular, the high cost of warming up the system when something malfunctioned in the experiment on the initial cooldown, in which case all 13 L were lost. With our system, the initial cooldown is completed entirely by the closed-cycle cooler and uses no external helium at all.

During a recent intensive 24-day period of running the cryocooler, with 345 hours of actual data taking, we used \$77 worth of helium gas. Using our previous liquid-helium system, this run would have cost around \$6,000! (We note that the cost of the *electricity* to run the 5 kW compressor during this period was around \$170. However, this cost is usually borne by the institution and not the investigator!)

5. Summary

We have constructed a cryogenic system that uses a pulse-tube cryocooler to liquefy helium gas, provided from an external source, into a small pot. The pot is then pumped to a temperature around 1.2 K. The temperature stability of the system is 25 μ K (rms) when the pot is full. The cooling power of the system depends on the helium flow rate, which can be varied by adjusting the pressure of the incoming helium. A maximum

cooling power of 27 mW was measured at a helium flow rate of 0.6 mmol/s. The cooling power as a function of flow rate is well explained by an isenthalpic model of liquefaction through a capillary. The operating cost of our cryogenic system is very low, using only about \$0.24 worth of helium (and \$0.50 of electricity) per hour.

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