Challenges in Cryocooling

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Abstract. This paper is the personal view of the author on the achievements of the field of cryocooling in the past and the challenges that it is facing today.

1. Introduction and Past performance
It is now more than 100 years ago that Kamerlingh Onnes liquefied helium for the first time.[1] This achievement has been the topic of several books and publications. The most recent one is the book by D. van Delft.[2] The setup is given in figure 1. There are four dewars for air and three for hydrogen. The hydrogen container above the helium cryostat is pumped to a low pressure so that the temperature is about 15 K. There are throttling valves for hydrogen and for helium. This is a very complicated system, especially if we keep in mind that the equipment that is needed to liquefy the air and the hydrogen, is not shown.

Nowadays temperatures in the 4K region are reached using Gifford-McMahon (GM) coolers and pulse tube refrigerators (PTRs). The left schematic in figure 2 represents a two-stage GM-refrigerator. It was invented by K.W. Taconis in 1950 [3] and turned into a practical and commercial cooler by McMahon and Gifford in 1960.[4] It consists of a compressor, an aftercooler, two buffer volumes, a rotary valve and a two-stage regenerator/displacer which is moved up and down by a driving mechanism. The right-hand side of figure 2 represents a two-stage GM-type pulse tube refrigerator (PTR). The idea of this form of PTRs comes from Mikulin et al.[5]. The GM-type PTR resembles very much the GM cooler but now the regenerator does not move. Instead two tubes, four valves, and two buffer volumes are added to the system. A description of the basic operation of GM and PTRs can be found in a review article by De Waele.[6]

If we compare figures 1 and 2 we see immediately that nowadays, reaching temperatures below 4K has become much simpler. This achievement has taken advantage of the development of materials with a high heat capacity below 10 K as initiated by Toshiba.[7]
Figure 1 Schematic diagram of the helium liquefier of Kamerlingh Onnes. Blue is air, green is hydrogen, orange is helium, and pink is (warm) alcohol. The lighter colors are gas; the darker colors high-pressure gas or liquid.

Figure 2 Schematic diagram of a two-stage GM-refrigerator (left) and a two-stage GM-type pulse tube refrigerator (right).
Figure 3 Time dependence of the no-load temperature of a two-stage GM.[8]

Figure 4 Temperature-pressure diagram of $^4$He. The red line is an isentrope, the blue lines represent the $\lambda$-line and the $\alpha=0$ line. The indicated pressure oscillation is the same as used in Ref.8 and figure 3.

But there is more: figure 3 gives the time dependence of the no-load temperature of a two-stage GM as measured by Bao et al.[8] It can be shown that under the experimental conditions of Ref.8, the expansion and compression of the helium at the cold end is adiabatic and reversible, so the specific entropy of the helium is constant.[9] Figure 4 is the temperature-pressure diagram of $^4$He showing the isentrope of $s=1.407$ J/gK (this is the specific entropy at 2.09 K and 24 bar obtained from Ref.[10]) together with the $\lambda$ line and the line where the isobaric expansion coefficient $\alpha$ is zero. On the right side of the $\alpha=0$ line $\alpha>0$, as usual, but on the left side $\alpha<0$. That means that in this region of the Tp-diagram, the $^4$He warms up during expansion and cools during compression.

In the experiment the pressure oscillates between 9 and 24 bar. During the pressure variation the Tp-dependence follows the isentrope. The experimental minimum temperature of figure 3 of 2.055 K agrees
nicely with the theoretical value in figure 4 where $\alpha$=0. The observed second maximum which occurs at the minimum pressure, of about 2.066 K is a bit lower than the theoretical value of 2.077K, derived from figure 4, but this can well be due to the fact that the experiment hits the $\lambda$-line! So nowadays the $^4$He cryocoolers really reach the lowest possible temperature.

![Pressure-temperature diagram of $^3$He](image)

Figure 5 Pressure-temperature diagram of $^3$He. The red lines are isentropes, the blue lines represent the melting line (m), and the line where $\alpha$=0.

Figure 5 is the TP-diagram of $^3$He with isentropes, the melting curve, and the $\alpha=0$ line obtained from Ref.11. The results obtained by Jiang et al. in the PTR from Giessen agree very well with the isentropes.[9][12]. The minimum temperature reached by the Giessen group was 1.27 K. The $\alpha=0$ line in figure 5 also represents the minimum temperature that can be reached with $^3$He. It varies from 0.5 to 1.4 K, so, theoretically, there is still room for reducing the no-load temperature from 1.27 K to temperatures well below 1 K.

2. The invisible cooler

As we saw in the previous section the progress in cryocooling has been impressive. Nowadays it is easy to obtain temperatures below 4 K and the lowest temperatures are at, or close to, the theoretical low limit. But that does not mean our job is finished. In fact we are still far away from the so-called invisible cooler. That is a cooler which is an essential component of some large equipment but is invisible for the user. The list of requirements is long: the cost, mass, volume, input power, noise, level of vibrations and EM interferences should be low. There should be no condensed ice or water. Accessories such as vacuum pumps and cooling water should be avoided. There should be no maintenance or cryofluid supply. It must work in all orientations, and, finally it should be turn-key, so it should operate without skilled cryogenic
assistance. In this respect the development of dry systems, which operate without cryofluid, has made superconducting magnets and dilution refrigerators [13] much more convenient and are a big step in the right direction. Also the discovery of high-Tc superconductors has made our life a bit easier. However, due to the long list of requirements, potential low-temperature technology will have a hard time for breaking through if there is a reasonable room temperature alternative.

To some extent the invisible cooler already exist: very few people know that, in the heart of the detector of the Planck mission that produced the marvelous overview of the background radiation, there was a dilution refrigerator that cooled the sensor to 0.1 K. And perhaps the best example of invisible coolers is in MRI equipment that makes scans of the human body. The patients have no idea that they are lying in the bore of a superconducting magnet which is submerged in a bath of liquid helium at 4.2 K.

3. What can be done with standard technology?

If we want to find out what can be done with more or less standard technology the so-called Strobridge diagrams can be helpful.[14] These have been updated in 2002 by Ter Brake and Wiegerinck.[15] Since this is already 16 years ago the diagrams now are incomplete and need an update. I just show the diagrams to clarify the principle about how they could be used.

In figures 6,7 and 8 each point represents a cooler with specified properties. The values depend on the low temperature. In this example I choose for 80 K. Each plot contains a cloud of points. Reference 15 was focusing on average trends, but here I will focus on the best values i.e. the lowest input power $P_{in}$, mass $M$, and volume $V$. With the necessary uncertainty these are: $P_{in} = 10Q_c$ W/W; $M = 10P_{in}$ kg/kW; $V = 0.2M$ liter/kg.

![Figure 6 Input power versus cooling power at 80 K. The red line represents $P_{in}=10Q_c$ W/W.](image-url)
Figure 7 Mass as function of the input power. The red line represents $M=10P_{in}$ kg/kW.

Figure 8 Volume as function of the mass. The red line represents $V=0.2M$ liter/kg.
Combination of best practices gives for a cooling power of 100 W@80K: $P_{in} = 1.0$ kW, $M = 10$ kg, and $V = 2$ liter. These values can be a source of inspiration for a designer to find out what should be possible with more or less standard technology. However, it may not be realistic to combine all best values in one machine. The low-hanging fruit has already been taken. Perhaps this is the reason why, presently, progress is slow.

4. Main topics at the moment

Some intriguing questions at the moment are:

Why are high-frequency coolers at VLT so inefficient?
The GM and PTRs at 4 K operate at frequencies in the 1 Hz region. Going to higher frequencies may lead to smaller coolers since less heat has to be stored in the regenerator per cycle. However, so far, going to higher frequencies leads to lower system performance. It is important to know why this is so, since this can show the way how high-frequency coolers can be made more efficient.

Why is the COP of VLT coolers so low?
The Carnot COP is $T_L/(T_a - T_L)$, so, ideally, 1 W cooling power at 4.2 K should require only 69 W compressor power. In reality, however, GM's and PTRs that produce 1W@4.2K use about 7 kW; about two orders of magnitude more. A factor of 4 is due to the dissipation in the compressor and the rotary valve, leaving still a factor of 25 discrepancy. The real-gas effect [16] is an important reason but one has the feeling that there should be ways to get around that. The high efficiency of the cooling system of the LHC[17] suggests that turbo-Brayton coolers, with lots of compressors and expanders, are the solution, but here we come in conflict with e.g. the cost requirement. Perhaps new construction techniques, such as 3D printing, can resolve this problem.

What causes the instability in high-aspect regenerators?
The relations governing the behavior of GM-coolers and PTRs are basically one dimensional. That means that the cooling power of optimized coolers is proportional to the area of the cross section of the regenerator and the pulse tubes perpendicular to the flow, keeping the lengths the same.[9] So large cooling powers need regenerators with large diameters. Hence the aspect ratio becomes large. In these high-aspect ratio regenerators instabilities have been observed. See e.g. Ref.18. The reason for this instability is, up to now, not well-understood.

So far we have discussed improving cryocoolers by improving existing technologies, but perhaps totally new concepts are needed. So forget about helium, regenerators, etc. In this context I would like to mention the cooling of atomic systems in 1995 which evolved separate from the conventional low-temperature technology.[19,20] The atoms are cooled first with lasers and then through so-called evaporative cooling (where the evaporation is not from liquid to gas, but high-energy atoms from the gas escape over an energy barrier). Thus extremely low temperatures have been reached in a large variety of gases. Unfortunately, these systems become unstable in mechanical contact with other systems, so they can't be used to cool other objects.

Laser-induced fluorescent cooling of solids [21] is an interesting alternative way for cooling but the presence of a high-energy laser beam combined with modest cooling power make it unlikely that this technique can compete with cryocoolers as we know them.
Another cooling technique, which differs from standard cryocooler techniques, is the suppression of the Brownian motion of mechanical resonators with a high quality factor. In these resonators the thermal motion is fairly well predictable on the short term, so, by measuring its velocity and position, a force can be applied to slow down the motion. This is done in optomechanics [22] for cooling resonant modes of nanowires [23], mirrors [24], and even of a 2 ton gravitational wave detector from 4.2 K to 0.17 mK.[25]

The problem with this technique is that the system is not in internal equilibrium. The quoted temperatures apply to the vibration mode in question.

Thermoelectric effects, such as the Peltier effect, are very attractive as coolers since they have no moving parts, nor cryofluid, nor do they require a compressor. However, they do not seem to be good candidates for coolers which produce higher cooling powers due the high value of the Faraday constant. This is the electrical charge per mole protons and equal to about $10^5 \text{C/mol}$. So e.g. a fairly large electrical current of 1 A corresponds with a small molar flow rate of 10 μmol/s with the correspondingly low cooling power.

5. Conclusion
In the recent past the progress in the field of cryocooling has been impressive: the construction is basically very simple, turn-key systems are available which allow the nonspecialized user to apply superconducting magnets, dilution refrigerators, etc. without any problem, and temperatures down to 2.2 K are readily available. However, for many potential applications such as in superconducting motors, the invisible cooler seems to be far away. With a lot of hard work only modest progress is made. Perhaps it is time for new concepts. It is an encouraging thought that everything that is not forbidden by the laws of physics can be realized in practice.

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