Reaching Low Temperatures

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Abstract: This paper will introduce the working principle of 5 macroscopic cooling methods and their limits. The cooling methods are sorted by their reached temperature and the previous method is often used as a pre–cooling system.

I. EXPANSION ENGINES

The cooling circuit of an expansion machine has five steps:

1. A gas is compressed in a compressor and heats up in the process.
2. The gas is cooled down to ambient temperature by a cooler.
3. The gas flows through a counterflow heat exchanger and then expands adiabatically in a slightly braked turbine. The temperature of the gas decreases.
4. This cooled gas is in thermal contact with the to be cooled material.
5. The gas flows through the counterflow heat exchanger in the opposite direction and pre–cools the still compressed gas from step 3.

The Systems has to stay above the gas' critical temperature. Which limits the temperature that can be reached. Usually ^{4}He is used because of its low critical temperature of 5.19 K[1][2] and availability. For the adiabatic temperature reduction from T_1 to T_2 it holds:

$$T_1 = T_2 \left(\frac{p_2}{p_1}\right)^{(\kappa-1)/\kappa} \tag{1}$$

(with $\kappa = C_p/C_V$ and $\kappa = 5/3$ for monoatomic- and $\kappa = 7/5$ for diatomic gases[1][3][4]).

II. JOULE-THOMSON EXPANSION

This cooling method uses, that the internal energy of the gas is volume dependent. It is therefore **not** an ideal gas. Joule-Thomson expansion can be used for cooling or heating. Whether the gas heats up or cools down during expansion depends on the Joule-Thomson-coefficient.

$$\mu_{\mathrm{JT}} = \left(\frac{\partial T}{\partial p}\right)_H \tag{2}$$

($\mu_{JT} > 0$ for cooling $\mu_{JT} < 0$ for heating[1][3])
This method is often used for the liquefaction of gases. The temperature limit for ^{4}He is $T \approx 4.2$ K.

III. HELIUM BATH CRYOSTATS

In Helium bath cryostats evaporation of helium is used to keep a constant temperature of $T \approx 4.2$ Kelvin[1][3]. The helium is stored in Dewar vessels, which are made of vacuum separated shells and used to minimize thermal conductance. The latent heat of evaporation of helium is 2.6 kJ l^{-1}[1]. Helium bath cryostats can be pumped to reach lower temperatures (consumption of 40 % of the helium to reach 1.3 K[1]).

Clausius-Clapeyron

$$\frac{\partial p}{\partial T} = \frac{L}{\Delta V T} \tag{3}$$

with $\Delta V = V_{gas} - V_{liquid} \approx V_{gas}$ and the ideal gas law $pV = nRT$

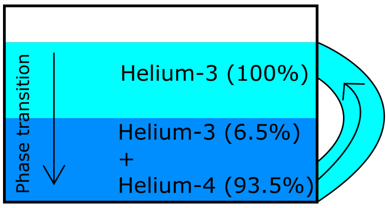
$$\frac{\partial p}{\partial T} = \frac{L}{RT^2} p \tag{4}$$

is a differential equation with solution

$$p(T) = p_0 e^{-L/RT}. \tag{5}$$

It holds that $\dot{Q} \propto p \propto e^{-L/RT}$[1]. As the temperature drops, so does the cooling power. This leads to a lowest achievable temperature of $T \approx 1$ K.

IV. DILUTION REFRIGERATION



There are two stable isotopes of Helium. ^{3}He and ^{4}He. ^{3}He is very rare and a fermion[2], ^{4}He is a boson[2] and therefore they behave very differently at low temperatures. ^{3}He obeys Fermi statistics and the energy rises with the number density of the ^{3}He atoms. This leads to a maximum amount of ^{3}He in a mixture of ^{3}He and ^{4}He (about 6.5 %)[1]. A phase separation between a mixture and a lighter phase of pure ^{3}He follows. The ^{3}He atoms in the lighter pure phase have a lower entropy than the ^{3}He in the mixed phase. By removing ^{3}He out of the mixed phase, ^{3}He of the lighter pure phase makes a phase transition into the mixed phase, taking thermal energy from the system. The different vapor pressures of ^{3}He and ^{4}He are used to ensure that only ^{3}He is removed from the mixed phase[5]. Temperatures down to $T \approx 0.01$ K can be reached.

V. MAGNETIC REFRIGERATION

This cooling technique takes advantage of the fact that the spin entropy of the cooling material is magnetic field dependent[2][1].

1. A magnetic field is turned on. The spins align themselves according to a magnetic field. While the spin entropy decreases, the total entropy of the system is conserved. Therefore, the temperature of the material increases.
2. The added heat is removed by a pre–cooling system. The magnetic field is constant.
3. The magnetic field decreases and the cooling material is thermally isolated. Thermal energy causes the spins to overcome the field. The spin entropy in the material rises, while total entropy of the system is conserved. The temperature of the material decreases.
4. The material is brought in thermal contact with the environment to be refrigerated.

With this method temperatures down to $T \approx 1 \times 10^{-6}$ K can be reached.

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