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An integrated mixed refrigeration cycle for pre-cooling of refrigeration below 25 K

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Abstract. Two trends can be found in current large-scale cryogenic projects. The first is the ever-increasing capacity requirements, while also a shift towards cooling demands at higher temperatures is observed. Conventional helium cycles require the use of oil flooded screw compressors, which are limited in efficiency, capacity, and reliability. Reverse-Brayton cycles with neon-helium mixtures deliver efficient refrigeration at a temperature above the dew point of neon, but cannot be applied to the cooling of conventional superconductors. This paper describes an approach where oxygen as a heavier gas allows the use of turbo-compressors viable. The oxygen is separated and used for providing refrigeration at higher temperature levels.

1. Introduction

Large physics experiments such as ITER or the FCC project rely on increasing energies for pushing the bounds of today's knowledge. With the energy levels involved in the systems, also the cryogenic heat loads are increased. Besides the increasing demand at LHe temperatures, also a higher share of heat loads in the temperature range 40 K to 80 K can be observed. In the past, high capacity systems were designed as modified helium Claude cycles with a Brayton stage for the higher temperature range. To overcome the limited efficiency of oil injected screw compressors, newer designs, e.g. the cryoplants for ITER and the FCC-hh [1] have additional Brayton cycles with turbo compressors. The use of the later is made possible by using either nitrogen (ITER) or a mixture of neon and helium (FCC-hh) as a gas with a higher apparent molar weight. This gas can be compressed in a reasonable number of centrifugal stages. While these Reverse-Brayton cycles also improve the efficiency of the lower temperature pure helium cycles by providing the pre-cooling, it would be desirable to have a cycle only with turbo compression for the higher temperature range and the liquid helium part. Such a cycle is expected to have a higher overall efficiency, and improved reliability and reduced number of components. A system where a heavier component is mixed to helium and removed by liquefaction and phase separation was described by Beddome [2]. His approach was to use a relatively high boiling heavier component with a normal boiling point above 170 K, e.g. R-12 or propane. These components, which show a significant Joule-Thomson effect without pre-cooling, are used for providing part of the pre-cooling. Such a system has the disadvantage that for systems, that have a high refrigeration and a relatively low liquefaction load, the benefit of the heavier component is limited. The reason for this is that the heavier component requires an energy input for compression as well, which can only be used for cooling in the temperature region of the boiling



temperature of the respective heavier component. One strategy to overcome this would be to use a heavy gas in small amounts to achieve the desired apparent molar weight of the mixture. With this strategy, the additional exergetic expense would be small. However, there is no gas fulfilling the requirements of a low triple point pressure, low global warming potential and low ozone depletion potential. In this paper, a cryogenic cycle having a heavier component with a normal boiling point in the range of the above mentioned loads is described.

2. Choice of heavier component

The removal of the heavier component is eased by a low triple point pressure, which corresponds to the partial pressure of the component after cooling to the triple point. Table 2 lists the cryogenic gases. A low triple point pressure can be found for fluorine and oxygen. While fluorine has a higher molar weight than oxygen, it is highly reactive and not considered a workable refrigerant. While oxygen is also highly reactive in concentrated form, the dangers associated with its use can be controlled by a sufficiently low concentration. A mixture of helium and 20 mol-% oxygen would have a higher required ignition energies compared to air [3]. The apparent molar weight of this mixture is 9.6 g/mol. Assuming a pressure coefficient of unity and a circumferential speed of 300 m s^{-1} , this mixture could be compressed from 1 bar to 20 bar in 21 centrifugal compressor stages. These could be arranged in four casings, where each two can be arranged in tandem configuration. With higher circumferential speed, the number of stages and eventually compressors can be reduced.

Table 1. Properties of the cryogenic fluids, data from RefProp [4]

fluid	M [g/mol]	T_{NBP} [K]	T_{trip} [K]	p_{trip} [kPa]
hydrogen	2.0	20.3	14.0	7.358
neon	20.2	27.1	24.6	43.368
fluorine	38.0	84.9	53.5	0.239
oxygen	32.0	90.1	54.4	0.146
nitrogen	28.0	77.2	63.2	12.520
carbon monoxide	28.0	81.5	68.2	15.537
argon	39.9	87.2	83.8	68.891

3. Process design

A principal flow scheme is shown in figure 1. The high pressure stream is cooled from ambient to

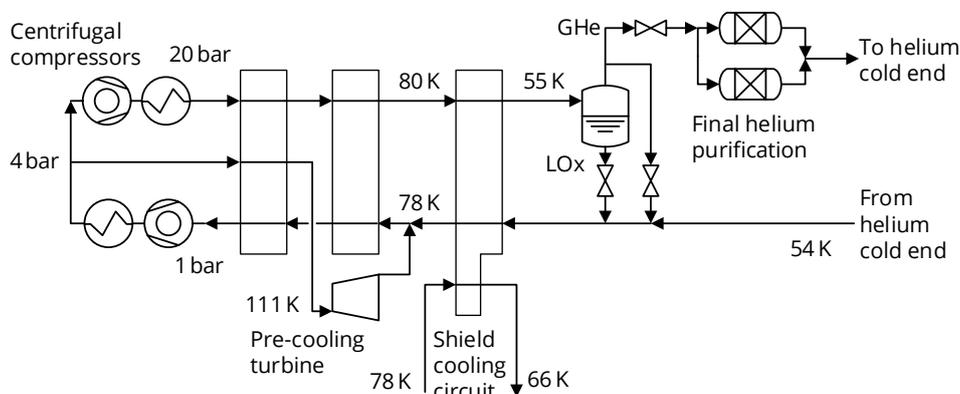


Figure 1. Principal flow scheme of the cycle

55 K. A close approach to the triple point pressure can be achieved by an appropriate design of the condenser. A relatively high fin spacing allows for the solidification of some oxygen without largely increasing the pressure drop. By the formation of solid oxygen the thermal resistance of the heat exchanger increases and thus a higher temperature difference to the cold side is restored. At 55 K temperature, the theoretical partial pressure of oxygen in helium, calculated by assuming an ideal mixture, is 178 Pa. Experimental data [5] are available down to 70 K but already indicate that the actual value is only about 1.2 times higher than theoretical, as can be seen from figure 3. The condensed oxygen is drained in a phase separator. The remaining oxygen of about 220 ppm in the high pressure helium stream is removed by either pressure swing adsorption or in a reversing heat exchanger.

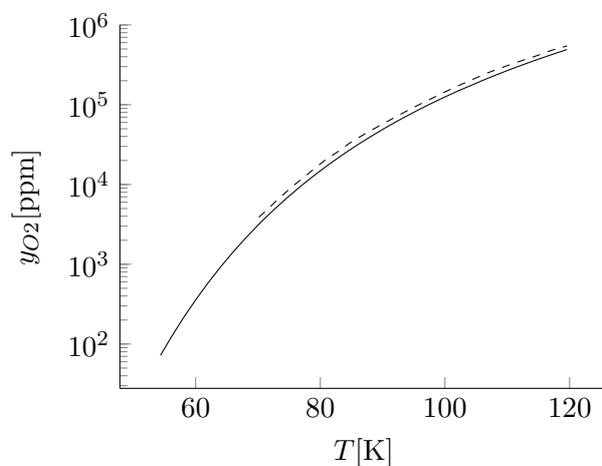


Figure 2. Residual content of oxygen in helium, dashed line experimental data from [5], solid line theoretical values

The molar exergy invested in the compression of the oxygen is about the same as for the helium. Thus one fifth of the exergy invested for compression would be lost if the oxygen was not used for providing part of the refrigeration. Since the oxygen has to be completely liquefied, a Claude cycle can be used for providing the refrigeration power which is then transformed by the liquid oxygen to a lower temperature. The liquefaction of oxygen begins at 104 K. Therefore the turbine inlet should be near this temperature. Usually, helium cycles use turbines between the high pressure and the intermediate pressure. In this case, it is beneficial to expand from the intermediate pressure to the low pressure, since this allows for a lower turbine outlet temperature without potentially dangerous condensation in the turbine. The pre-cooling turbine is also required for the start-up of the cycle. In order to avoid that oxygen enters the helium part of the refrigerator, the valve in front of the final purification stage is closed during start-up, instead the high-pressure gas flow is throttled directly to the low-pressure side. The pre-cooling turbine then allows to cool down the cycle until 55 K are reached at the inlet of the phase separator. Subsequently, the valve can be opened and pure helium admitted to the cold end of the cycle. The refrigeration capacity carried by the liquid oxygen can be used at temperatures above about 66 K. Figure 3 shows the temperature profiles in the heat exchangers between 120 and 55 K for an exemplary cycle. The flow rate through the turbine is twice the one of the high pressure compressor. With the turbine inlet at 111 K, and the extraction of the cooling power between 66 and 78 K, a close approach of both curves is possible. With this cycle, 60 % of the refrigeration exergy are available at the higher temperature level, and 40 % can be used for the

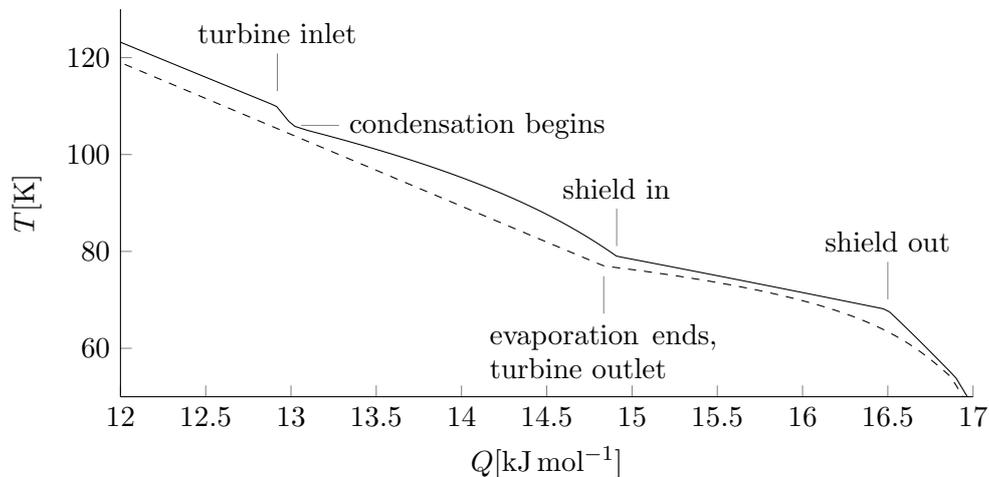


Figure 3. Temperature profiles for the condenser/liquefier part, relating to one mole of the initial mixture in the high pressure stream, solid: warm composite curve, dashed: cold composite curve

pure helium part. The ratio can be changed by an adjusted oxygen content, which on the other hand affects the design of the turbo-compressor.

4. Safety considerations

The use of oxygen as a refrigerant is unusual until now and raises some questions about safety. Generally can it be stated, that liquid oxygen is used in many industries with a good safety record, if appropriate safety measures are taken. In the case of this concept, the oxygen content in the compressor stream is limited to 20 mol – %, as already stated above. Nevertheless, the pure oxygen in the phase separator and the condenser/evaporator makes it necessary to introduce a safety concept. The first step is to limit the absolute amount of oxygen as much as possible. Furthermore, combustible particles must not enter the cold box, which is ensured by filters after the high pressure compressor and in the cold box. If the concept is applied to an accelerator within a tunnel, a 55 K cut is possible, with the helium/oxygen cold box on the surface and a pure helium cold box in the tunnel, similar to the current concept for FCC-hh [1].

5. Conclusions

The application of turbo compressors for cryogenic cycles operating at liquid helium temperatures becomes feasible by using a mixed refrigerant of helium and oxygen. the oxygen is separated at 55 K and provides refrigeration at about 66 to 78 K. The helium is purified at 55 K and can then be used for refrigeration at LHe temperature levels.

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