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TOWARDS COST-TO-PERFORMANCE OPTIMISATION OF LARGE SUPERFLUID HELIUM REFRIGERATION SYSTEMS

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Abstract

The field range of superconducting devices may be extended by lowering their operating temperature, using superfluid helium refrigeration systems which have to deliver working pressures down to 1.6 kPa. The corresponding pressure ratio can be produced by integral cold compression or using a combination of cold compressors in series together with "warm" compressors at room temperature. The optimisation of such a system depends on the number, arrangement and characteristics of cold and warm machines as well as on the operating scenario and turndown capability. The aim of this paper is to compare relative investment and operating costs of different superfluid helium cryogenic systems, with the aim of optimising their cost-to-performance ratio within the constraints of their operating scenario.

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Towards Cost-to-Performance Optimisation of Large Superfluid Helium Refrigeration Systems

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The field range of superconducting devices may be extended by lowering their operating temperature, using superfluid helium refrigeration systems which have to deliver working pressures down to 1.6 kPa. The corresponding pressure ratio can be produced by integral cold compression or using a combination of cold compressors in series together with “warm” compressors at room temperature. The optimisation of such a system depends on the number, arrangement and characteristics of cold and warm machines as well as on the operating scenario and turndown capability. The aim of this paper is to compare relative investment and operating costs of different superfluid helium cryogenic systems, with the aim of optimising their cost-to-performance ratio within the constraints of their operating scenario.

1 INTRODUCTION

Large projects based on applied superconductivity push the required performance close to the limit of the state-of-the-art superconductors, and therefore may have to use superfluid helium refrigeration. By lowering the operating temperature, the current density in superconducting magnet cables and the quality factor of superconducting acceleration cavities can be significantly improved [1].

2 POSSIBLE REFRIGERATION CYCLES AND BASIC ASSUMPTIONS

Producing large refrigeration capacity at 1.8 K requires the use of cold compressors to compress helium up to a pressure at which “warm” compressors at room temperature become practically feasible. The overall pressure ratio of 80 can be produced either by a “mixed” compression scheme based on a combination of cold compressors in series with warm compressors, or by “integral cold” compression based on multi-stage cold compressors. Figure 1 shows the two corresponding generic schemes, which for the purpose of the discussion, may be split in two parts. The first part concerns the 1.8 K refrigeration unit producing the overall pressure ratio. The second part is a standard 4.5 K refrigerator, producing non-isothermal refrigeration between 4.5 K and a temperature Tr, which directly depends on the cold compressor pressure ratio (CCR). In the “mixed” cycle, the 1.8 K refrigeration unit is constituted of a cold compressor box (CCB) housing the cold compressors (CC), a phase separator (PS), counter-flow heat exchangers and 80 K adsorbers (ADS) for air impurity removal, as well as a warm compressor station (WCS) containing “warm” compressors (WC) and the oil removal system (ORS). In the “integral cold” cycle, the 1.8 K refrigeration unit is only constituted of a cold compressor box containing the CCs and the phase separator.

To proceed with the analysis, we made the following assumptions, based on experience with recent such systems [2,3]. The cold compressors, of the hydrodynamic type (centrifugal or axial-centrifugal), have a maximum pressure ratio of 3 and a corresponding isentropic efficiency of 75 %. The pressure drop in the low-pressure stream of the counter-flow heat exchanger corresponds to 10 % of the absolute pressure. The total pressure drop in the high-pressure side including the ORS, the heat exchanger and the adsorbers is equal to 0.1 MPa. The temperature difference at the cold end of the heat exchanger is 5 K.

The 4.5 K refrigerator, which has to cope with other loads, is assumed to have a total capacity of 10 kW at 4.5 K ; the different costs related to the 1.8 K refrigeration are calculated in accordance.

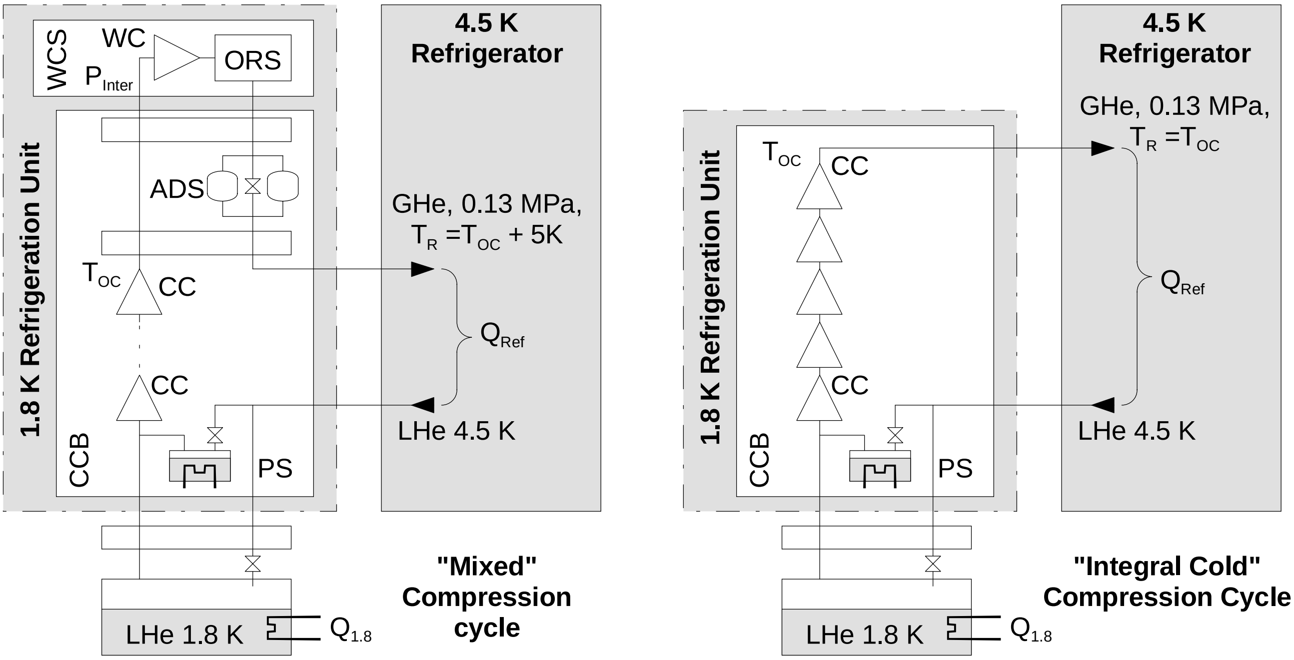

Figure 1 Possible schemes for producing large-capacity 1.8 K refrigeration

3 INVESTMENT COST

The total investment cost can be split into three components, estimated separately in the following.

The cost I1 (Equation 1) of the 4.5 K refrigerator required to absorb the non-isothermal load Q_{Ref} created by the 1.8 K refrigeration unit between 4.5 K and T_R, is estimated from the average specific investment cost of 10 kW @ 4.5 K refrigerators [4], and from the isothermal refrigeration capacity at 4.5 K exergetically equivalent to Q_{Ref} (Figure 2).

The cost I2 (Equation 2) of the 1.8 K refrigeration unit (excluding the cold compressors proper), is derived from the average investment cost of 4.5 K refrigerators [4] having comparable volumetric process flow-rate. The lumped reduction of 0.45 MCHF accounts for the absence of turboexpanders in the CCB. In the case of integral cold compressor, I2 is taken as 50 % of the cost of the CC.

The cost i3 (Equation 3) per single CC stage is based on $\dot{m}_0$, T_0, P_0, the inlet design conditions of each CC, and W_0, the corresponding compression power. The first term represents the influence of turbomachine size, and the second term accounts for the power rating of the drive. This equation is scaled from prototype machinery tested at CERN [3].

$$I1 = 0.876 \cdot r \cdot Q_{1.8}$$

I1 in MCHF for $Q_{1.8}$ in kW (1)

$$I2 = 25.7 \cdot \left(\frac{Q_{1.8}}{P_{Inter}} \right)^{0.6} - 0.45$$

I2 in MCHF for $Q_{1.8}$ in kW and P_{Inter} in kPa (2)

$$I3 = \sum_n i3 = \sum_n \left[0.62 \cdot \left(\frac{\dot{m}_0 \cdot \sqrt{T_0}}{P_0} \right)^{0.33} + 0.071 \cdot W_0^{\;0.33} \right]$$

I3 in MCHF for $\dot{m}_0$ in kg/s, T_0 in K, P_0 in kPa and W_0 in kW (3)

Based on the above, Figure 3 shows the relative investment cost of superfluid helium refrigeration as a function of the CCR. The “integral cold” cycle (CCR = 80) yields the minimum overall investment cost.

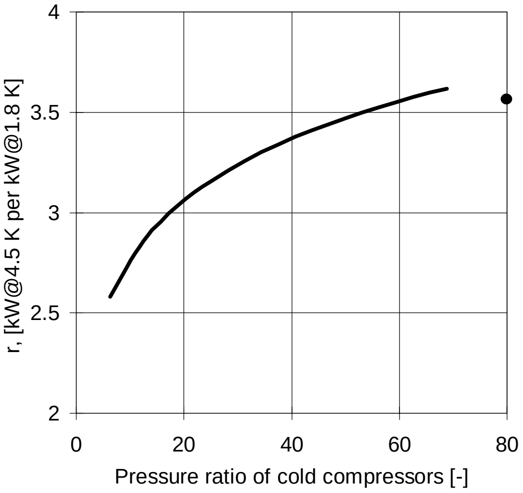

Figure 2 Specific equivalent 4.5 K load induced by the 1.8 K refrigeration unit

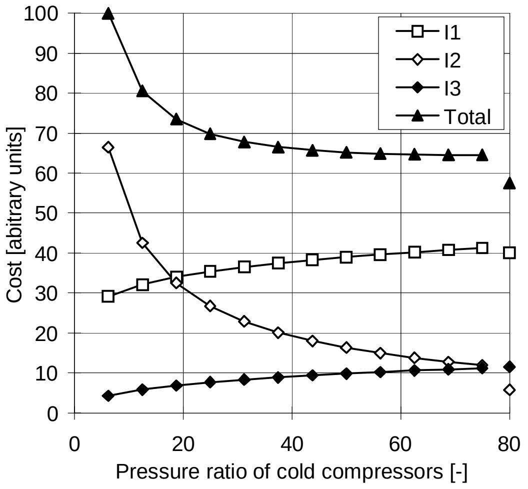

Figure 3 Investment cost of superfluid refrigeration systems

4 OPERATING COST

The operating cost of the superfluid helium refrigeration system depends on the type of cycle used and on its ability to adapt efficiently to turndown capacity. In “mixed” cycles, the warm volumetric compressors allow to cope with reduced flow by decreasing the CCR. Figure 4 gives the WC isothermal efficiency used for the calculation of electricity consumption of the 1.8 K refrigeration unit. For the “integral cold” cycle, turndown capacity is very limited and the reduced flow-rate has to be compensated by extra vaporisation in the phase separator, thus maintaining the operating cost almost constant. The running cost of the attached 4.5 K refrigerator is calculated as a function of its effective COP given in Figure 5 [5]. Figure 5 also shows the operating cost as a function of the turndown capacity for different values of the CCR. At 33 % of turndown, the operating cost of “mixed” cycles amounts to 60 % of that of “integral cold” cycles.

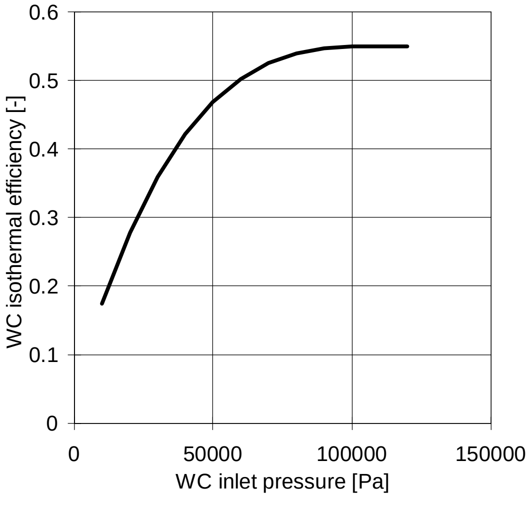

Figure 4 Isothermal efficiency of warm compressors

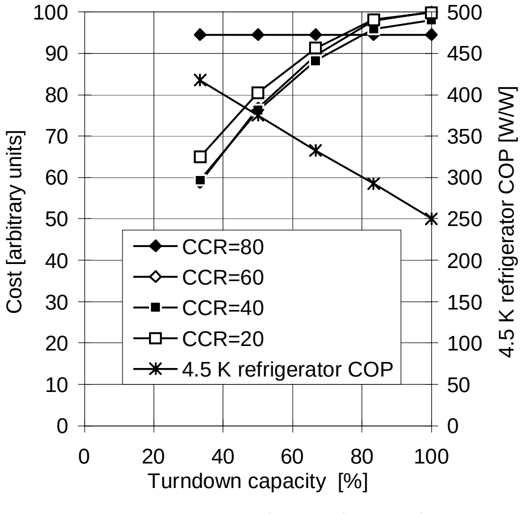

Figure 5 Operating cost of superfluid refrigeration systems

5 THE LHC CASE

The overall integrated cost of superfluid helium refrigeration finally depends on the operating scenario and the price of electrical energy. Taking the LHC [6] over 10 years as an example, it is foreseen to operate 26400 hours at 33 %, 26400 hours at 66 % and 13200 hours at 100 % of installed capacity with an average price of electricity of 60 CHF/MWh [4]. Figure 6 shows the corresponding investment and operating costs as a function of the CCR. For the LHC, systems based on “mixed” cycles show comparable total cost to those based on “integral cold” cycles, as long as the CCR exceeds 35. The savings on operating cost offsets the slight difference in investment cost. The choice of a “mixed” cycle for the LHC also included other considerations [7,8], like making use of existing 4.5 K refrigerators, than overall cost optimisation alone.

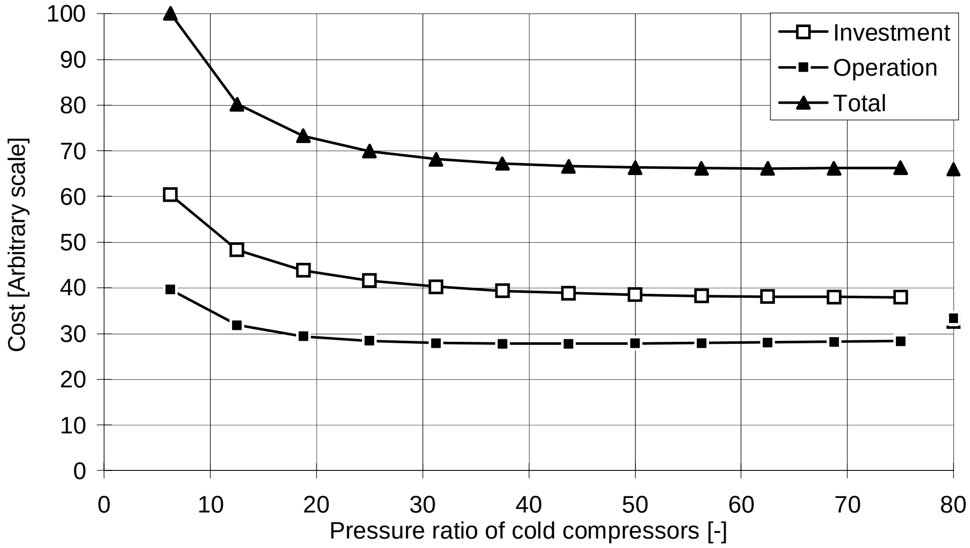

Figure 6 Investment and operating costs of the LHC superfluid helium refrigeration system

6 CONCLUSION

The application of basic engineering thermodynamics, together with semi-empirical rules and scaling laws based on recent experience with industrially-produced systems, has permitted to estimate investment and operating costs of large-capacity superfluid helium refrigeration. By including probable operating scenarios and taking into account turndown capability of the equipment, it is further possible to proceed to an overall optimisation. Although the real engineering case is much more complex, this simple approach confirms that, for the sake of economy, a significant fraction (typically one half) of the pressure ratio must be produced by cold compressors.

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