Thermodynamic and cost-effectiveness analyses of chosen cooling loops for local production of saturated superfluid helium in large cryogenic systems

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Abstract. Large scientific facilities applying HeII technologies usually use the Joule-Thomson expansion for the final production of saturated superfluid helium at their cryogenic users. The users are usually supplied with subcooled liquid helium at 4.5 K and 3 to 4 bar(a). Then, to produce HeII, the 4.5 K helium is precooled in a local heat exchanger and throttled to a sub-atmospheric pressure below 50 mbar(a). This final throttling goes along an isenthalpic line which leads to the zone of wet vapour at the quality of 15.9%. The efficiency of this process can be strongly affected by additional heat loads, which may result in a significantly higher quality of the throttled helium. This imperfection can be partly decreased by using a local subcooler or by splitting the expansion process into two phases with an intermediate point around 1.2 bar(a). However, these solutions require additional components, such as phase separators with some instrumentation and another throttling valve. The paper presents the comparative thermodynamic analysis of the three identified cooling loops. Potential savings due to thermodynamic efficiency improvements are verified against the capital costs for different operation times.

1. Introduction
Large scientific facilities applying HeII technologies usually use the Joule-Thomson expansion for the final production of saturated superfluid helium at their cryomodules and magnet cryostats. Required cooling power is usually delivered by the flow of subcooled liquid helium at a temperature of 4.5 K and pressure of 3 bar(a) via a long distribution system. Then, in the most basic local cooling loop, the 4.5 K helium is precooled in a heat exchanger to a temperature of 2.2 K and throttled to a sub-atmospheric pressure below 50 mbar(a) to produce superfluid helium. Such a scheme is used at European Spallation Source ERIC for cooling the ESS linac cryomodule cavities down to 2 K in a superfluid helium bath at a pressure of 31.3 mbar [1]. Here, the final throttling goes along an isenthalpic line which leads to the zone of wet vapour at the quality of 14.45%, which gives a specific cooling capacity of 19.9 W/g @2K. A similar local cooling loop was applied for cooling the 1.9 K superfluid helium loops of the LHC superconducting magnets. The cold helium at a temperature of 4.6 K and pressure 3.6 bar(a) is precooled and throttled to a pressure of 16 mbar to produce superfluid helium at a temperature of 1.8 K [2]. This basic local cooling loop has a number of advantages. In this case, the quality of the produced 1.8 K helium is equal to 19.55%, which gives a specific cooling capacity of 18.66 W/g @1.8K.
The efficiency of this basic local cooling loop can be significantly affected by some additional heat loads in the distribution line and cryomodules. These heat loads may lead to higher temperatures in the heat exchanger as well as in the inlet to the JT valve, which may result in a significantly higher quality of the throttled helium and lower specific cooling capacity. To balance the given heat loads to the cryogenic users there is a need for increasing the mass flow rate of cold helium, which may require higher energy consumption at the cryoplant.

This imperfection can be solved by using one or more local subcoolers. Such a solution was applied in the Accelerator Module Test Facility at DESY in Hamburg, Germany. This facility is supplied with cold helium from a cryoplant located around 200 m from the test stands. The cryoplant produces subcooled liquid helium at 4.5 K and 4 bar(a), which is transferred to the facility via a multichannel cryogenic transfer line. In order to compensate heat load to the transfer line, the test stand is equipped with a local subcooler. A certain fraction of the cold helium is throttled in the subcooler phase separator kept at a pressure of 1.2 bar(a), whilst the rest goes through an integrated heat exchanger to the so-called 5 K forward line [3].

Another solution is to split the expansion process into two phases with an intermediate point around 1.3 bar(a). It has been applied in local cooling loops of the half-wave resonator cryomodules of the Rare Isotope Accelerator Complex for On-line Experiments RAON under construction in Daejeon, South Korea. The RAON cryoplants will supply sub-cooled liquid helium at 4.5 K and 3 bar(a). In each cryomodule, the cold helium will be expanded by the first J-T valve to 1.25 bar(a) in a phase separator to produce liquid helium at a temperature of 4.45 K. Next, the 4.45 K helium is cooled down to 2.2 K in a heat exchanger and later throttled in the second J-T valve to a pressure of 36.1 mbar to produce superfluid helium at 2.05 K. The 4.45 K liquid helium is used for cooling down an additional thermal shield which is located between the cavities and their 40-60 K thermal shield. The additional thermal shield is kept at 5 to 8 K and is cooled down by thermostophoning the 4.5 K in a cooling circuit terminated at the outlet from the phase separator to the 5-8 K gaseous helium return line.

Both the modified local cooling loops require additional components, such as an extra throttling valve, a phase separator or a subcooler, a thermal shield, as well as some instrumentation (temperature sensors and level gauges). The additional components make the improved cooling loops more expensive. This additional capital costs can be obviously balanced by savings in the operating costs if the operation time is sufficiently long.

The paper presents the comparative thermodynamic analysis of the three cooling loops in respect to the initial, intermediate and final thermodynamic states of helium. Potential savings due to thermodynamic efficiency improvements are verified against the capital costs for different operation times.

2. Description of the identified cooling loops

The identified 3 cooling loops for local production of 2K helium are from here on named as cooling loops #1, #2 and #3. The flow scheme of cooling loop #1 is shown in Figure 1. It is the simplest loop for efficient production of superfluid helium. It consists of a Joule-Thomson valve and a heat exchanger and requires one supply line and one return line. The supply line shall deliver subcooled liquid helium at a pressure above the critical pressure (2.26 bar(a)) to avoid 2 phase flow and at a reasonably low temperature. Usually, this temperature is specified to not exceed 5.5 K to make the isenthalpic expansion efficient. For higher inlet temperatures the limiting factor is the available cooling power of the returning sub-atmospheric pressure helium in the heat exchanger. All cold parts of the cold helium cooling loop, including the superfluid helium vessel, which contains superconducting cavities and/or magnets, are surrounded by a thermal shield for minimising heat loads to 2 K and 4.5 K parts. The shield is usually cooled by a cold helium vapour at a temperature of 40-60 K or by liquid nitrogen at 77 K.

Cooling loop #2 is schematically shown in Figure 2. Beside the heat exchanger and 2K throttling valve (JTV2), the loop includes an additional throttling valve (JTV1) and a subcooler. The subcooler is a phase separator equipped with an integrated heat exchanger. A small fraction of cold helium is throttled in JTV1 to a pressure of 1.1 bar(a) to 1.3 bar(a) to produce a liquid helium bath of 4.3 K.
to 4.5 K. The rest of cold helium is directed into the integrated heat exchanger, where it is cooled down to the required temperature before being cooled to 2.2 K in the main heat exchanger, placed upstream to the 2K throttling valve.

Cooling loop #3 also includes an additional throttling valve (JTV1) and a phase separator. Its flow scheme is schematically shown in Figure 3. Here, the cold helium is throttled to the subatmospheric pressure in two stages, with an intermediate pressure in the phase separator at a value slightly above the atmospheric pressure.
The saturated liquid helium is directed from the phase separator to the heat exchanger and further to JTV2. This liquid helium flows also into the 5–8 K thermal cooling loop, which ends in the upper part of the phase separator. Helium flow in this loop is driven by thermosyphon effect.

All the identified cooling loops require some instrumentation, such as temperature and pressure sensors for measurements of helium properties in the supply lines and level gauges for controlling the helium level in the HeII vessels. For example, in cooling loops #2 and #3, their phase separators require a certain control of the liquid helium level as well, in order to avoid a risk of pouring liquid helium into the He return line.

### 3. Thermodynamic analysis of the identified cooling loops

The proposed thermodynamic analysis of studied processes applies the exergy method and is focused on evaluating losses due to the irreversibility of thermodynamic processes and finally the exergy efficiencies of the identified cooling loops [7, 8, 9]. The exergetic efficiency ($\eta_{ex}$) is defined as the ratio of the potential useful exergy output ($Ex_{out}$) to the potential useful exergy input ($Ex_{in}$):

$$\eta_{ex} = \frac{Ex_{net}}{Ex_{in}} = \frac{Q \left( 1 - \frac{T_0}{T_{out}} \right) \ln \left( \frac{T_{out}}{T_{in}} \right)}{m \left( (h(T_{out}, P_{out}) - h(T_{in}, P_{in})) - T_0 (s(T_{out}, P_{out}) - s(T_{in}, P_{in})) \right)},$$

where: $T_0$ is the ambient temperature (assumed as equal 290 K), $T_{in}$ and $T_{out}$ – temperatures at the outlet and inlet of the analyzed system or subsystem, respectively, $Q$ – heat given to the system at $T_0$, $m$ – helium mass flow rate, $h$ – enthalpy and $s$ – entropy.

In order to facilitate the comparison of the cooling loops, the thermodynamic analysis is performed with an assumption that the loops are used for cooling a representative cryomodule which is 10 m long and its 2 K helium vessels and their piping are subjected to static and dynamic heat loads of 20 W and 30 W, respectively. In case of cooling loop #3, the static heat load is decreased by 5 W, which are taken by the 5-8 K cooling thermal shield. The calculations were carried out for the characteristic points shown in Figures 1, 2 and 3. It was also assumed that the pressure losses in the cryogenics lines are negligible, but in the heat exchanger, the helium pressure drops by 100 Pa. Tables 1 and 2 show some example results for cooling loops #2 and #3, respectively, for temperature in the He supply line at 5 K. In case of cooling loop #1, the corresponding results will be the same as for points F, G, H, I and K as in cooling loop #2.

**Table 1. Example results of numerical calculations for cooling loop #2**

| Point | $T$ (K) | $p$ (Pa)       | $m$ (kg/s) | $h$ (kJ/kg) | $s$ (kJ/kg K) |
|-------|---------|----------------|------------|-------------|---------------|
| A     | 5,000   | 3,000E+05      | 2,937      | 14,5549     | 4,2038        |
| B     | 5,000   | 3,000E+05      | 2,500      | 14,5549     | 4,2038        |
| C     | 4,998   | 1,300E+05      | 0,437      | 14,5549     | 3,8903        |
| D     | 4,998   | 1,300E+05      | 0,437      | 30,4696     | 8,0703        |
| E     | 5,000   | 3,000E+05      | 2,500      | 14,5549     | 4,2038        |
| F     | 4,998   | 3,000E+05      | 2,500      | 11,7700     | 3,6188        |
| G     | 2,200   | 3,001E+05      | 2,500      | 5,0247      | 1,6179        |
| H     | 1,997   | 3,100E+03      | 2,500      | 5,0247      | 0,9495        |
| I     | 1,997   | 3,100E+03      | 2,500      | 25,0279     | 12,5945       |
| K     | 3,220   | 3,000E+03      | 2,500      | 31,7733     | 15,3076       |
Table 2. Example results of numerical calculations for cooling loop #3

| Point | T (K) | p (Pa)  | \( \dot{m} \) (kg/s) | h (kJ/kg) | s (kJ/kg K) |
|-------|-------|---------|-----------------------|-----------|------------|
| A     | 5,000 | 3,00E+05| 2.838                 | 14,5549   | 4,2038     |
| C     | 4,498 | 1,30E+05| 2.838                 | 14,5549   | 3,8903     |
| F     | 4,498 | 1,30E+05| 2.132                 | 11,6298   | 3,8903     |
| G     | 2,200 | 1,30E+05| 2.132                 | 3,9174    | 1,6293     |
| H     | 1,997 | 3,10E+03 | 2.132                 | 3,9174    | 0,9495     |
| I     | 1,997 | 3,10E+03 | 2.132                 | 25,0279   | 12,5945    |
| K     | 3,402 | 3,00E+03 | 2.132                 | 32,7403   | 15,5998    |
| L     | 4,498 | 1,30E+05| 0.266                 | 11,6298   | 3,8903     |
| M     | 4,508 | 1,30E+05| 0.266                 | 30,4505   | 8,0914     |

The total mass flow rate supplied to the cooling loop varies with the temperature in the He supply line as shown in Figure 4. For loop #1 it increases only by 10% with the inlet temperature rising from 4.5 K to 5.5 K, but for the modified loops the mass flow rate increase varies much stronger for different pressures in the subcooler and phase separator.

![Figure 4. Total mass flow rates versus the He supply inlet temperature](image)

The total power required by the refrigerator working in a temperature range between \( T_0 \) and \( T_{\text{out}} \) can be estimated using a ratio of the potential useful exergy input to the overall efficiency in respect to the Carnot cycle (\( \eta_{\text{Carnot}} \)):

\[
P_{\text{Refri}} = \frac{E_{\text{in}}}{\eta_{\text{Carnot}}}
\] (2)

In the considered temperature range this overall efficiency is assumed as equal to 27\%, just like in [9].

The distributions of total exergetic efficiencies and refrigerator power consumptions are presented in Figures 5 and 6. They show that cooling loop #3 is the most efficient in the entire temperature range.
Cooling loop #1 is very sensitive to the helium inlet temperature. Its exergetic efficiency is equal to 45% and drops by one third with the He supply temperature increase from 4.5 K to 5.5 K. The efficiency of cooling loop #2 drops by one fourth, but for cooling loop #3, it has the highest values and decreases much less, from 48.5% to 45%, or even from 51% to 46% in case of 1.1 bara(a) in the phase separator (instead of 1.3 bar(a)). Loop #3 requires from 8% to almost 15% less refrigeration power than loop #1.

4. Cost-effectiveness analysis of the identified cooling loops
The proposed cost-effectiveness analysis compares the savings in operating costs for the modified cooling loops against their additional capital costs. The savings are simply calculated based on the improvements of thermodynamic efficiencies ($\Delta P_{\text{Refri}}$), operating time and costs of used electrical power.
The unit cost of electrical power was assumed as equal to 0.06 EUR per kilowatt-hour, based on the average electricity price for industrial customers in European countries. For an operating time, it was assumed that the installations are in full operation 7000 hours a year.

The additional capital cost depends on the number of additional components and their unit prices, which can obviously vary on the number of procured components. Generally, the larger the number, the cheaper unit price. Therefore, the cost-effectiveness analysis was performed for three representative theoretical cryogenic facilities composed of 15, 30 and 60 cryogenic users (representative cryomodules), respectively. It was assumed that for the given sets of additional components, the discounts are at the level of 10%, 15%, and 20%. The estimated unit costs of the additional components in respect to the procured unit numbers are presented in Table 3.

Table 3. Estimated unit costs of the additional components in cooling loops #2 and #3 for different procured unit numbers, EUR

| Number of cryogenic users | Cooling loop #2 | Cooling loop #3 |
|---------------------------|-----------------|-----------------|
|                           | 15              | 30              | 60              | 15              | 30              | 60              |
| Discount                  | 10% 15% 20%     | 10% 15% 20%     | 10% 15% 20%     |
| JT valve 2                | 7 600           | 6 840           | 6 080           | 6 840           | 6 460           | 6 080           |
| Phase separator           | 2 200           | 1 980           | 1 870           | 1 980           | 1 870           | 1 760           |
| Subcooler’s heat exchanger| 300             | 270             | 255             | -               | -               | -               |
| He return line section    | 2 500           | 2 250           | 2 125           | 2 000           | 2 250           | 2 125           | 2 000           |
| 5-8K thermal shield       | 5 500           | -               | -               | 4 950           | 4 675           | 4 400           |
| 4.5K thermosyphon loop    | 2 500           | -               | -               | 2 250           | 2 125           | 2 000           |
| Level probe and controller| 2 700           | 2 430           | 2 295           | 2 160           | 2 430           | 2 295           | 2 160           |
| Controls                  | 500             | 450             | 425             | 450             | 425             | 400             |
| Total per 1 loop:         | 14 220          | 13 430          | 12 640          | 21 150          | 19 975          | 18 800          |
| Total per 1 installation: | 213 300         | 402 900         | 758 400         | 317 250         | 599 250         | 1 128 000       |

Since the temperature in the He supply line inlets to local loops tends to increase for longer installations, it was estimated that the average inlet temperature is equal to 4.6 K, 4.7 K, and 4.8 K, for the defined theoretical cryogenic facilities comprising 15, 30 and 60 cryogenic users, respectively. The comparison of cumulative operating cost savings against capital costs for the modified cooling loops is presented in Figure 7.

Figure 7. Comparison of cumulative operating cost savings against capital costs for the modified cooling loops
The additional unit cost of loop #2 has been estimated at 15.8 kEUR. For a set of 60 such loops (20% discount), the total cost of additional components drops to 12.6 kEUR. Then, the total cost of the additional components is estimated at 758 kEUR. The operating cost savings of this value can be reached only after 37 years of continuous operation. For shorter installations, the return times are even longer.

In the case of cooling loop #3, the additional unit cost has been estimated at 23.5 kEUR. For a respectively short cryogenic facility (150 m and 15 cryogenic users) their total additional capital cost is around 317 kEUR. This may be balanced by operating cost savings in 28 years of continuous operation. For larger facilities, the time of complete investment return can drop to around 20 or even 15 years for larger facilities, 300 m and 600 m in length with 30 and 60 representative cryomodules, respectively.

5. Conclusions
The paper presents the exergetic efficiency and cost-effectiveness analyses of three identified cooling loops for local production of superfluid helium in large cryogenic facilities. The cooling loop with the Joule-Thomson expansion process split into two phases and equipped with a 5-8 K thermal shield (actively cooled with the 4.5 K helium flow driven by thermosyphon effect) is characterized by a high exergetic efficiency and low required refrigeration power consumption. This loop is also the most expensive, however, its operating cost savings are very high. The savings can balance the total additional costs in the operating time of 15 to 20 years for a respectively large facility. Taking into account that the operating time of large scientific facilities can be even twice longer, cooling loop #3 looks very promising for reducing costs of future large HeII installations.

The return time can obviously vary considerably for different designs of cryogenic users and distribution systems, and especially for different geo-economic circumstances. Therefore, all design choices shall be supported by thorough and cost-effectiveness analysis, specific for local conditions.

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