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

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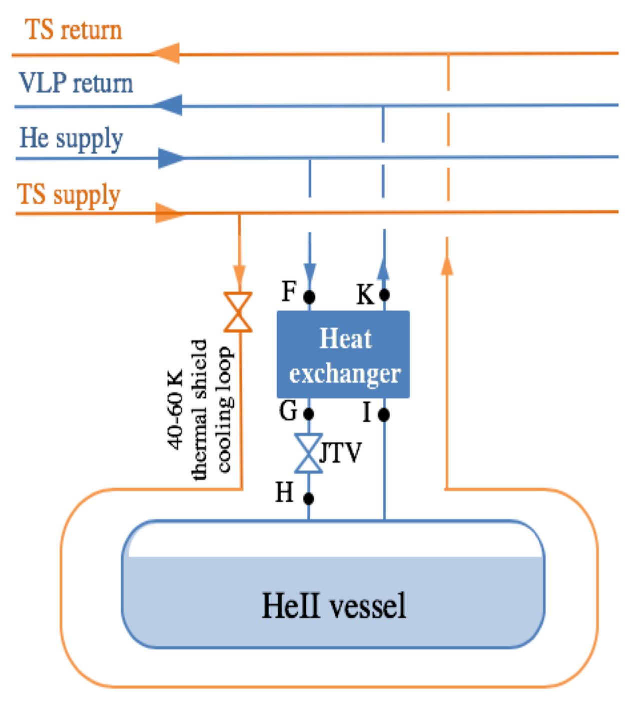
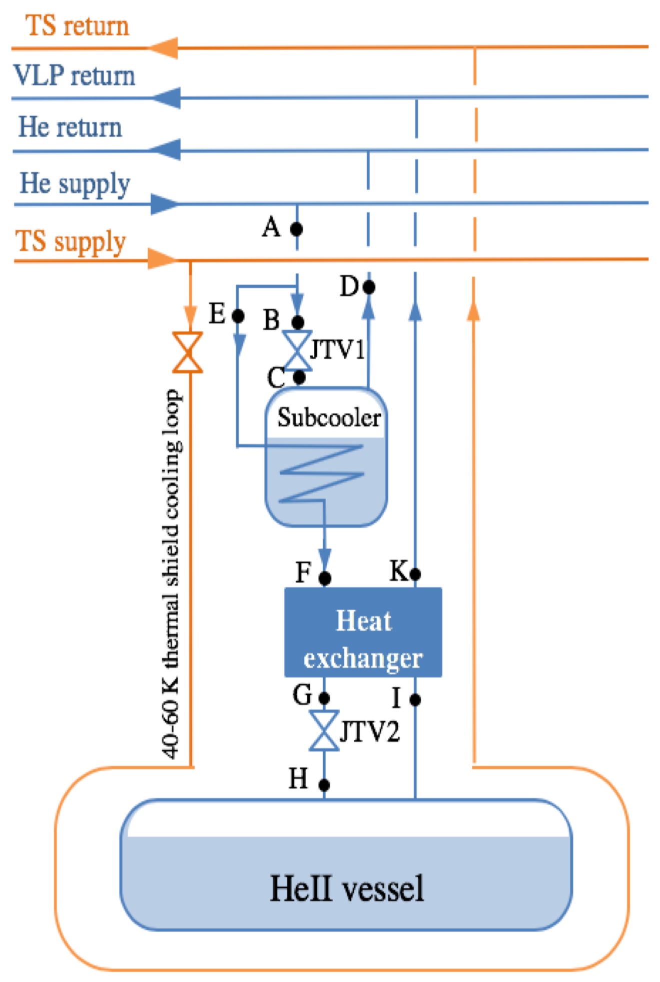
Introduction. Large scientific facilities applying HeII technologies usually use the Joule-Thomson expansion for the final production of superfluid helium at their cryogenic users. The users are usually supplied with subcooled liquid helium at 4.5 K and 3 bar(a). To produce HeII, the 4.5 K helium is precooled in a local heat exchanger and throttled to a pressure below 50 mbar(a). This final throttling goes along an isenthalpic line to wet vapor at quality around 15%, which gives a specific cooling capacity of 20 W/g @2 K. The efficiency of this process can be reduced by additional heat loads. This imperfection can be mitigated by using a local subcooler or splitting the expansion process into two phases, however, these solutions require additional components. The paper presents the comparative thermodynamic analysis of three identified cooling loops. Potential savings due to thermodynamic efficiency improvements are verified against the capital costs.

Cooling loop #1 is the simplest loop for a quite efficient production of HeII. It consists of a Joule-Thomson valve (JTV), a heat exchanger, supply and return lines and a superfluid helium vessel with super-conducting cavities and/or magnets. All cold parts are screened by a thermal shield, which is usually actively cooled by helium vapor at 40-60K.

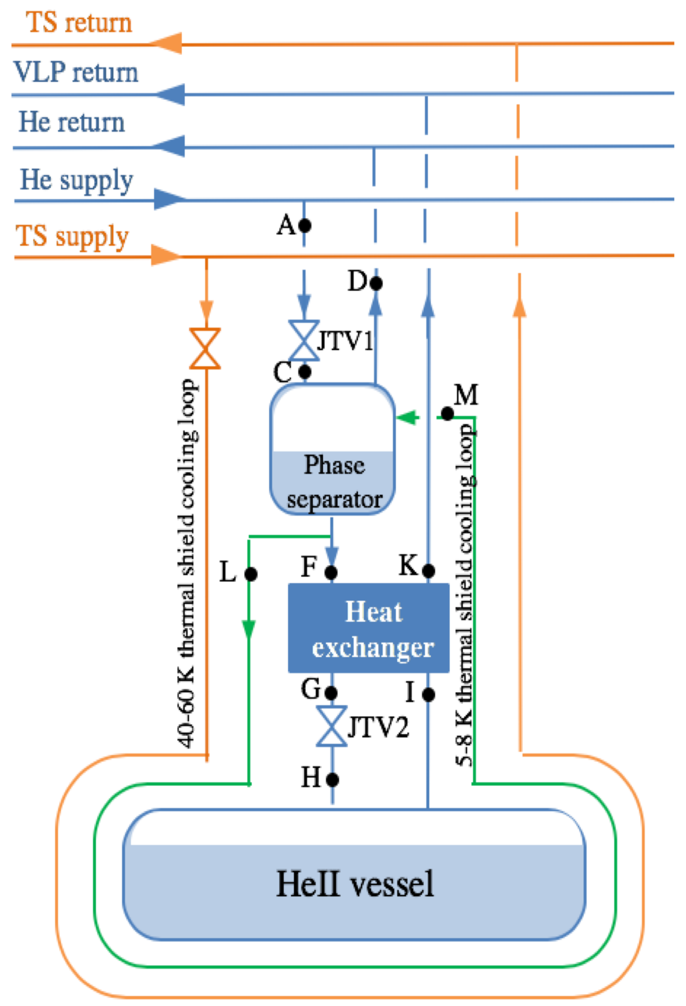
Cooling loop #2, beside the heat exchanger and 2K throttling valve (JTV2), includes an additional throttling valve (JTV1) and subcooler. The subcooler is a phase separator equipped with an integrated heat exchanger. A fraction of cold helium is throttled in JTV1 to a pressure around 1.2 bar(a) to produce a saturated helium bath, while the rest is directed to the integrated heat exchanger for precooling to 4.5 K before ultimate subcooling in the 4.5-2.2K heat exchanger.



Cooling loop #1



Cooling loop #2



Cooling loop #3

Cooling loop #3 includes an additional throttling valve (JTV1), a phase separator and 5-8 K thermal shield . The cold helium is throttled in JTV1 to a pressure of 1.1-1.3 bar(a) and flows to the phase separator. Then, it is directed to the heat exchanger and further to JTV2 for the production of HeII. A certain fraction of the 4.5K liquid helium is directed to the 5-8 K thermal shield cooling loop, where its flow is driven by thermosyphon effect.

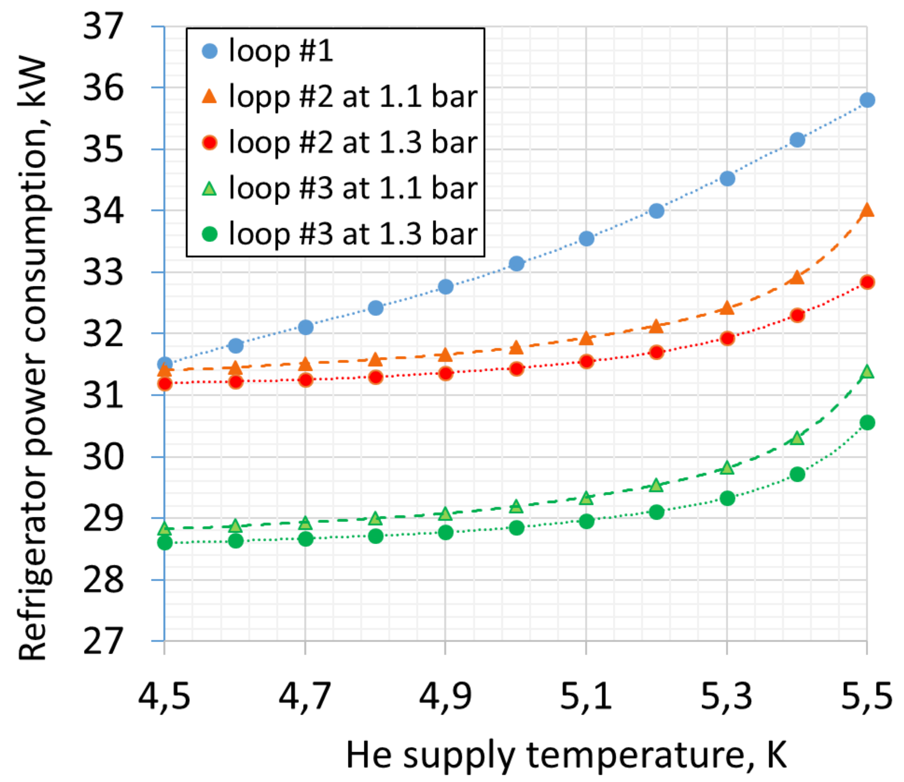
Exergy analysis was used for evaluating the effectiveness of cooling loops and losses due to the irreversibility of thermodynamic processes. The exergy efficiency η_{ex} is defined as the ratio of the potential useful exergy output to the potential useful exergy input:

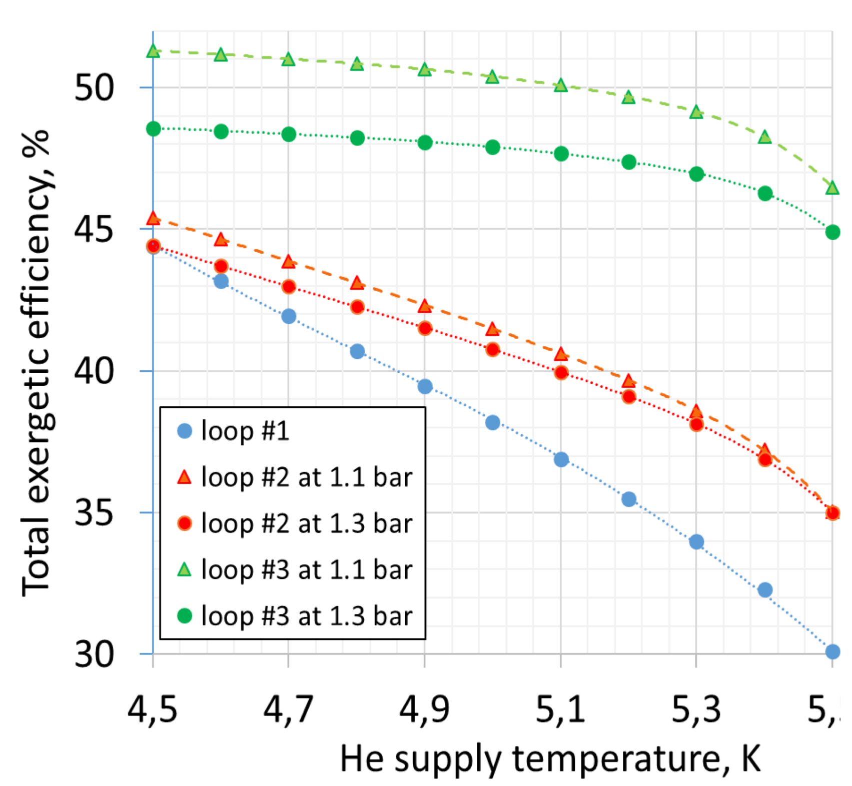
$$\eta_{ex} = \frac{Ex_{net}}{Ex_{in}} = \frac{Q\left(1-\left(\frac{T_0}{T_{out}-T_{in}}\right)\ln\left(\frac{T_{out}}{T_{in}}\right)\right)}{\dot{m}\,(\Delta h \; - T_0\,\Delta s)}$$

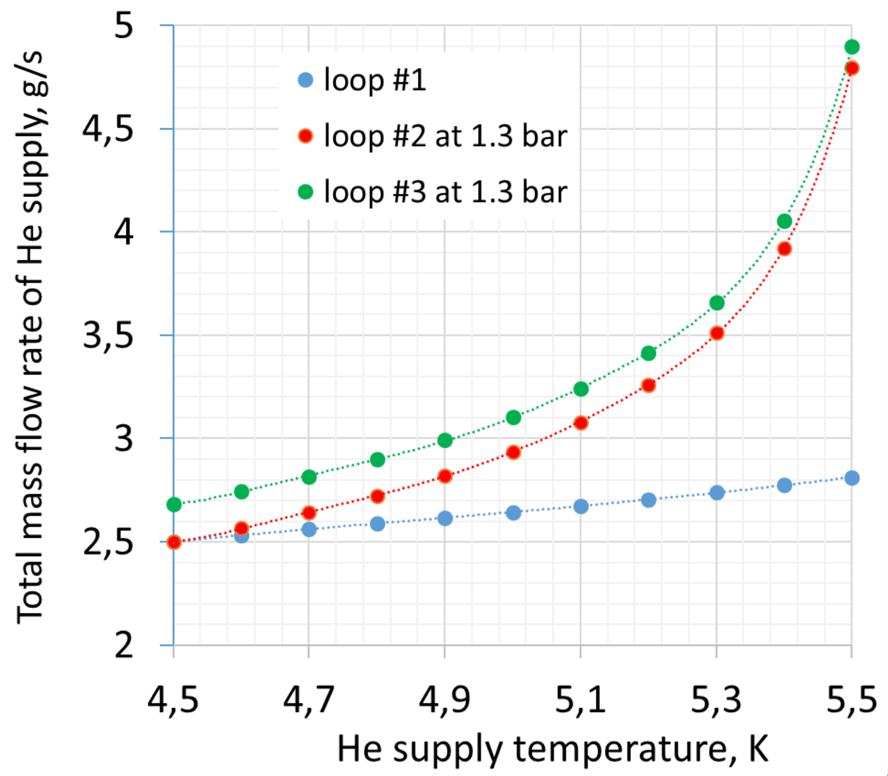
The total power required by the refrigerator working in a temperature range between T_0 and T_{out} can be estimated using a ratio of the potential useful exergy input to the overall efficiency in respect to the Carnot cycle:

$$P_{Ref} = \frac{Ex_{in}}{\eta_C}$$

In the considered temperature range it can be assumed as equal to 27%.



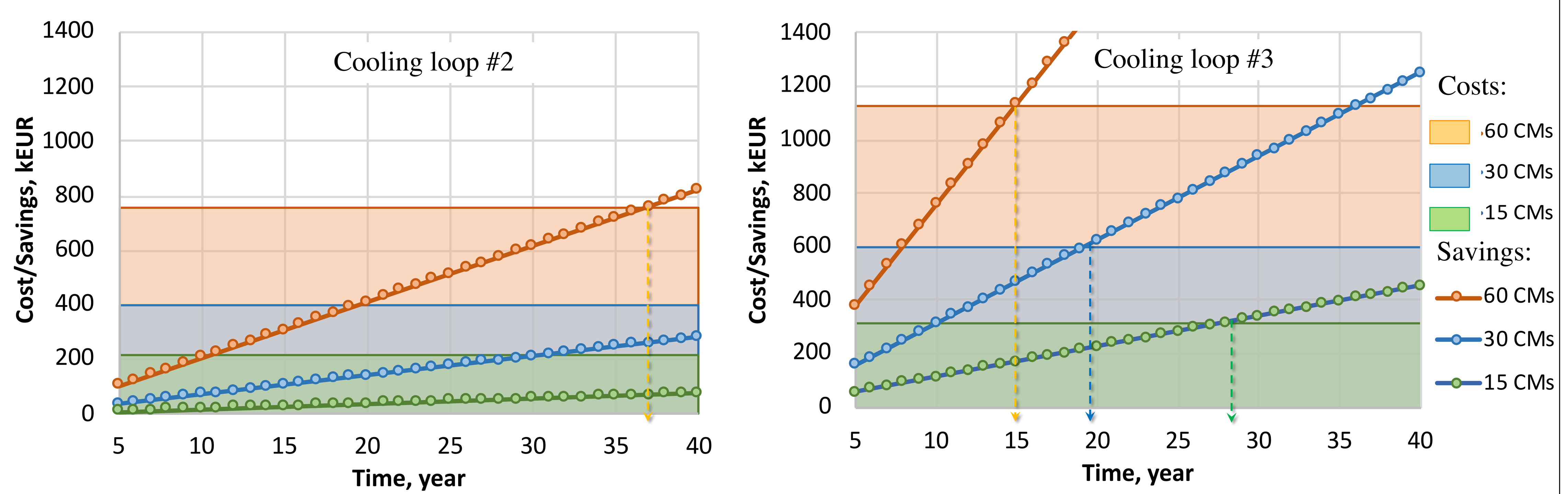




Cost-effectiveness analysis of the identified cooling loops compares the savings in operating costs for the modified cooling loops against their additional capital costs. The savings are simply calculated based on the improvements of thermodynamic efficiencies (ΔP_{Ref}) and costs of used electrical power (0.06 EUR per kilowatt hour). Additional capital costs depend on the number of additional components and their unit prices, which may differ for different numbers of the procured components (discounts!). The cost effectiveness analysis was performed for three representative theoretical cryogenic facilities composed of 15, 30 and 60 cryogenic users (cryomodules). It is assumed that each representative cryomodule is 10 m long and its static and dynamic heat loads are 20 W and 30 W at 2K.

Estimates of additional capital costs for the modified cooling loops, cost in EUR

		Cooling loop #2			Cooling loop #3		
Number of pieces	1	15	30	60	15	30	60
Discount	0%	10%	15%	20%	10%	15%	20%
JT valve 2	7 600	6 840	6 460	6 080	6 840	6 460	6 080
Phase separator	2 200	1 980	1 870	1 760	1 980	1 870	1 760
Subcooler's heat exchanger	300	270	255	240	-	-	-
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	400	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**



Comparison of cumulative operating cost savings against capital costs for the modified cooling loops

Discussion and conclusions. 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)). It shows that cooling loop #3 is the most efficient. It requires from 10% to 15% less refrigeration power in respect to loop #1. The additional unit cost of this loop has been estimated at 23.5 kEUR. For a respectively short cryogenic facility (150 m, 15 CMs) their total additional capital cost is around 317 kEUR, which may be balanced by operating cost savings in 28 years of continuous operation (7000 hours a year). 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.

The return time can obviously vary very much for different CM and CDS designs and different geo-economic circumstances, nonetheless, cooling loop #3 looks very promising for reducing costs of large HeII installations.