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Theoretical study on the efficacy of the cold compressor based cryogenic cycles

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Abstract. Cold compressor based cycles have emerged as practical necessity for sub 4.5K (sub atmospheric) large scale cryogenic systems as used in most modern high energy accelerators and tokamaks. The concept of cold compressor can be applied in a generalized way for even atmospheric (high pressure) cycles, if justified. A rise in temperature is exhibited at the exit of the cold compressor due to pressurization and the inefficiency involved in the process. This rise in temperature results in gain of sensible heat, and acts like a refrigeration load at that temperature. This loss can only be acceptable if other advantages of cold compressors are substantial. In the present work, it is tried to explore the possibility of using the emerged cold compressor technology for medium scale cryogenics. One of the objectives of the study is to develop a cold compressor based refrigeration cycle which can be implemented using the present infrastructure at Cryo-Technology Division, Bhabha Atomic Research Centre (BARC). In this endeavour, a cryogenic cycle analysis tool is developed and is validated against the process data available for 2K cryogenic plant at LHC. Three cold compressor based modifications are proposed to the presently installed modified Claude cycle based helium liquefier. These three cases are analysed and compared.

1. Introduction

High energy particle accelerators and plasma containments require superconducting radio-frequency (RF) cavities and high power superconducting electromagnets. These RF cavities and magnets work at very low temperatures typically at or below 4.5K. Use of superfluid helium in these applications enhances the performance by providing uniform cooling with high heat transfer rates and stable operation by suppression of the quench instability. All of these techno-economical requirements have made the 2K cryogenic systems a norm for these superconductor applications [1].

Large scale cryogenic systems below 4.5 K are based on sub atmospheric helium refrigeration cycles. The large difference between the density of gaseous helium at 4.5K and room temperature compels the use of cold compressor to enhance the plant compactness and economy. In case of cold compressors, helium is compressed when it is cold and dense, thus making the machines compact, however, the absence of heat sink for the compression process results in a rise in temperature. The rise in temperature due to practical compression process of the cold compressor with inefficiencies acts like a refrigeration load at that temperature. This loss can only be acceptable if it can be overcome by other advantages of the cold compressor. The present study tries to explore the use and efficacy of the emerging cold compressor technology for medium scale cryogenic cycles. One of the objectives of the study is to develop a cold compressor based refrigeration cycle which can be implemented using the present infrastructure at Cryo-technology division, BARC.

In the present work, a cycle simulation tool has been developed for cryogenic plants. The simulation tool is validated using the available data for the LHC cryogenic plant. In order to study the cold



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compressor efficacy for medium scale (few hundred Watts of equivalent refrigeration at 4.5K), helium liquefaction/refrigeration systems, three cold compressor based modifications are proposed to the modified Claude cycle based liquefier. The cycles are described along with the analysis, results and main conclusions.

2. Simulation tool for the cycle analysis

A simulation tool is developed for analysing cryogenic process cycles. The simulator is intended to solve for steady state solution using the overall and equipment level mass and energy balance equations along with equations related to equipment performance parameters. The operation state points and cycle performance along with basic sizing of the turbines and cold compressors can be computed using the tool. Moreover, this tool can be easily configured for different process cycles and process parameters. The inputs for the simulator are equipment efficiencies and pressure ratio for turbines and cold compressors, effectiveness values for heat exchangers, pressure drops, heat in-leaks and mass flow through the various equipments and valves. Although the pressure and mass flow rates are inputs to the simulator, these can be varied by the optimization sub routine either individually or simultaneously. Similarly, in case of multi stream heat exchangers, the mass participation of the streams can either be provided as input or it can be varied by the simulator to achieve equal exit temperatures in participating streams. The code is written in Microsoft Excel® VBA® and it uses HePak® for helium property evaluation. The process simulator and the optimisation subroutine are independently validated as described below.

2.1. Validation of the process simulator with thermodynamic cycle for cryogenic plant at LHC

In order to validate the code, the simulator is used to simulate the 2K refrigeration cycle used at LHC, CERN. The cold compressor diameters are also computed for this validation analysis. The cold compressor sizing in the simulator is based on optimum similarity parameters as per Balje curves [2]. Figure 1 presents the comparison of the reported temperature entropy (T-S) diagram for the LHC cycle with the T-S diagram obtained from the computation. It can be seen from figure 1 that the error in temperature computation is within fraction of a Kelvin at low temperatures and up to 3 Kelvin at high temperatures as compared to the reported values [3-4].

Figure 2 shows the schematic diagram of the 2 K refrigerator and flow diagram for the simulator. Table 1 shows the comparison of computed diameters with the diameters reported for cryogenic plant at LHC[5].

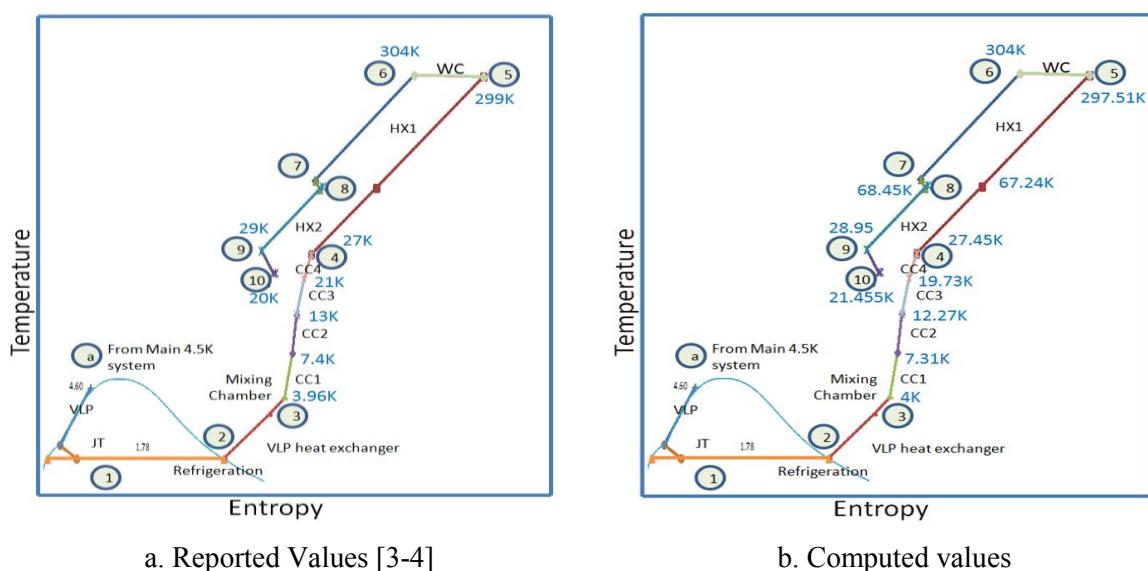


Figure 1. Comparison of reported and computed process cycle for cryogenic plant at LHC.

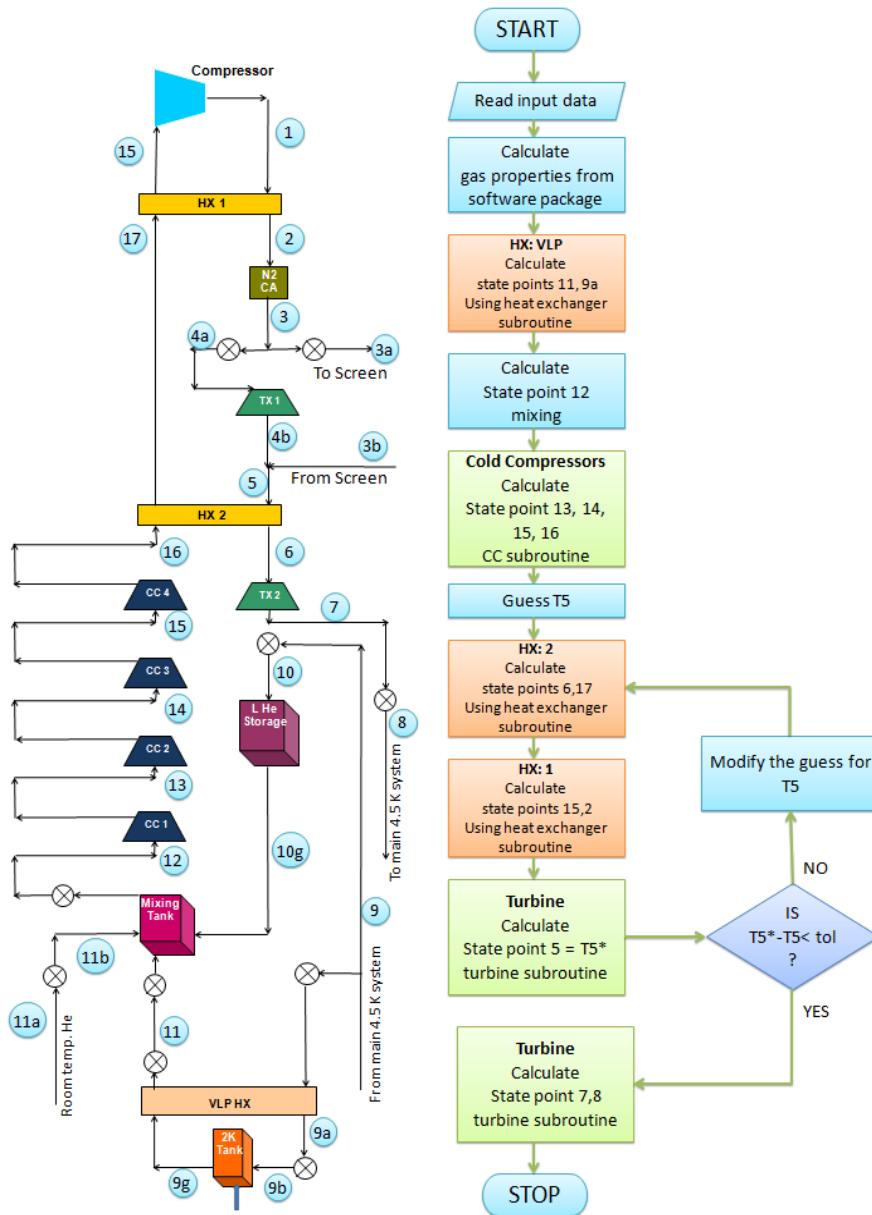


Figure 2. Flow diagram for 2K cycle computation

Table 1. Comparison of reported and computed diameters of the cold compressors for cryogenic plant at LHC.

Cold Compressor (CC)	Computed Diameter(mm) Installed Mode	Computed Diameter(mm) Normal Mode	Reported [5] Diameters(mm)
First Stage (CC1)	257	234	250
Second Stage (CC2)	165	151	165
Third Stage (CC3)	113	103	115
Fourth Stage (CC4)	107	95	105

2.2. Validation of the optimization subroutine

The optimisation sub routine is based on multi-dimensional Newton's method [6]. It can either be used to optimize a single parameter or multiple parameters simultaneously. The validation of the code is done using the classical isoperimetric problem [7], where it is required to find a curve maximising the enclosed area for a given perimeter. The problem is simplified for the validation case by taking extremising functional or optimisation goal as $(\text{Area}/\text{perimeter})^2$ and fixing the end points of the curve. In this validation case, both the x and y coordinates are considered for variation through the subroutine. In the initial guess solution, there is a discontinuity and the point distribution is kept non-uniform. The convergence of the solution is shown in figure 3. In 200 iterations, the nine point approximation to the curve reaches very close to the analytical solution, which is a circle. The optimisation goal is achieved within 2% deviation from the analytical solution.

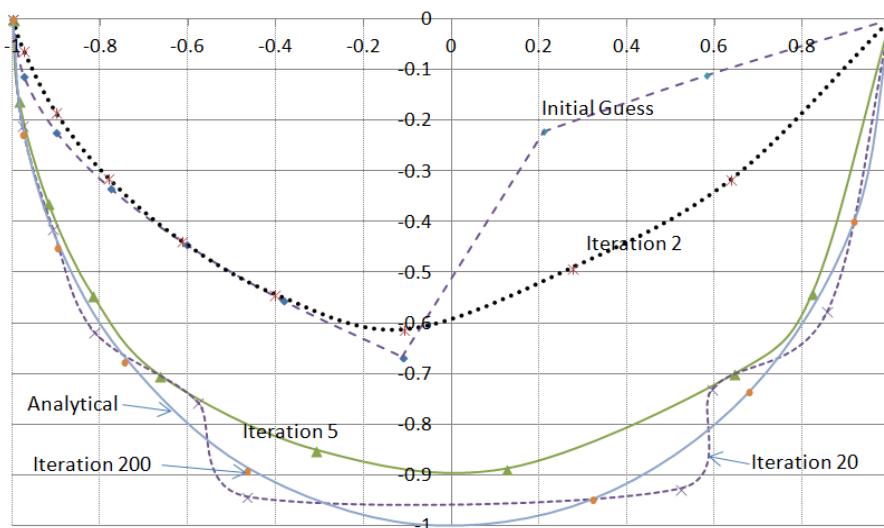


Figure 3. Convergence of the optimisation subroutine for modified Isoperimetric problem.

3. Study on the cold compressor based cycle at medium scale refrigeration capacity

3.1. Process study of 2K hybrid refrigeration cycle at medium scale refrigeration capacity

In this study, calculations are performed for a 2K hybrid refrigeration cycle similar in configuration as shown in figure 2. The process is analysed assuming medium scale refrigeration, which is possible to implement with the infrastructure presently installed at the Cryo-Technology division BARC. For this purpose, the mass flow rate through the cold compressor is limited to around 5 g/s. Table 2 shows the computed specific speeds (n_s) and rotational speeds of different cold compressor stages under two different cases.

Table 2. Results for medium scale 2K hybrid cycle

Cold Compressor (CC)	Assuming Similarity		Assuming the speed limit	
	n_s	n (Hz)	n_s	n (Hz)
First Stage (CC1)	0.89	1013	0.18	202
Second Stage (CC2)	0.89	2027	0.18	400
Third Stage (CC3)	0.89	3388	0.18	677
Fourth Stage (CC4)	0.78	3471	0.16	694

The specific speed used in this study is defined as per reference [2] in the following equation,

$$n_s = \frac{\omega \sqrt{V}}{(H_{ad})^{3/4}}$$

Where, ω is angular velocity of the cold compressor in rad/s, V is the volumetric flow at the inlet of cold compressor in m^3/s , H_{ad} is the adiabatic head available across the cold compressor in J/kg .

In the first case, the specific speeds (n_s) are chosen as per Balje curves [2]. In the second case, rotational speed limits are assumed similar to the LHC machine [4-5] and the specific speeds are computed in the reverse. In the first case, the rotational speeds of the cold compressors are too high and not practically achievable. In the second case, the specific speeds are too low to have a good efficiency as per Balje curves. Therefore, it is concluded that for medium scale implementation of cold compressor based cycles, other thermodynamic process options, which would rationalize cold compressor size and speed, should be investigated.

3.2. Process studies on cold compressor based modification to Claude cycle based liquefier

In the endeavour to search for cold compressor based medium scaled refrigeration cycles, three types of modifications using cold compressors are proposed to the presently installed Claude cycle based liquefier at BARC [8]. These modifications individually use single stage cold compressor. Each modification is considered as a separate case for this study and the cold compressor location in the process for these cases are shown in figure 4 as position-1, position-2, and position-3 respectively. It has been also been an attempt to chart the domain of operation of the cycle where cold compressor is useful in enhancing the capacity.

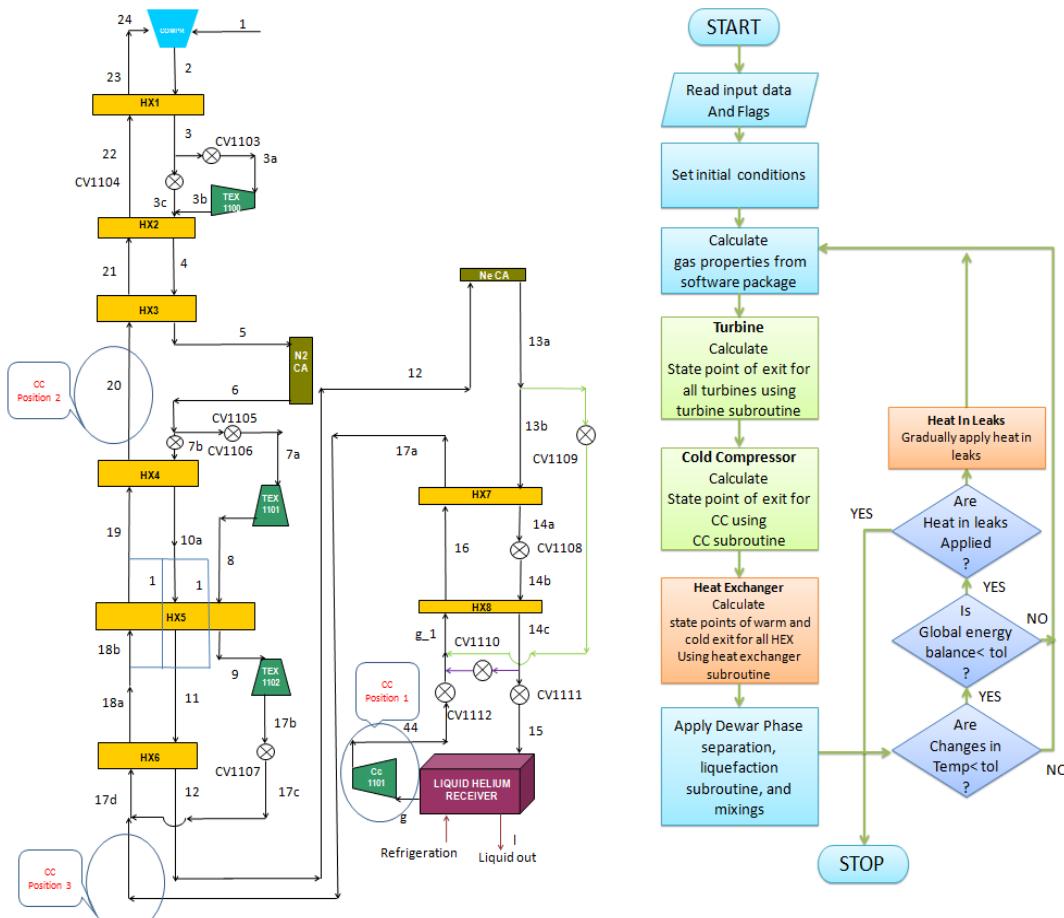


Figure 4. Schematic of the cold compressor based modifications to the Claude cycle liquefier and the flow chart of the simulator.

In Case-1, the Claude cycle is modified by placing the cold compressor at the position-1 marked in figure 4. The liquid helium formed after the Joule Thomson expansion is collected in the helium receiver vessel. In the LHe receiver vessel, the refrigeration load is applied. In case-1, helium vapour coming out from the LHe receiver vessel in the LP line is compressed by a cold compressor. The compressed gas is then fed back to the cold recovery circuit of the liquefaction cycle. In this case, the cold compression is at the lowest temperature and any inefficiency will result in highest loss of exergy. In case-2 (CC position – 2, figure 4), the cold compressor position is kept at higher temperatures to reduce the effect of cold compressor inefficiency. In this case, the cold compressor has to compress higher amount of gas compared to case1.

Case-3 (CC position – 3, figure 4) is proposed as a compromise between the above two cases. In this case, the cold compressor is positioned such that the mass flow will be similar to case-1, but the temperature will be higher than that computed in case-1 but lower than that in case-2.

In order to compare the results common inputs are assumed in all the cases. Table 3 details the inputs which are based on the references [3-4, 9]. Turboexpander and cold compressor efficiencies are assumed to be 65% in the analysis. The process compressor discharge pressure is assumed around 1.2MPa. For every case, thermodynamic cycles are optimised with the goal of maximum refrigeration capacity, for turbine and compressor pressures and mass flow distribution assuming the volumetric capacity of the process compressor as 1500 m³/hr to be constant (input to the problem).

Table 3. Inputs for the thermodynamic analysis. [3-4, 9]

Sr.	Equipment	Effectiveness/Efficiency	Heat In leak (W)	Pressure drop in HP stream (MPa)	Pressure drop in LP stream (MPa)
1	LP pipeline			-	0.004
2	HX1	0.95	5	0.005	0.01
3	HX2	0.95	3	0.003	0.01
4	HX3	0.95	4	0.002	0.008
5	HX4	0.85	2	0.001	0.005
6	HX5 IP	0.96	5	0.001	0.002
7	HX5 HP	0.96	0	0.001	0.002
8	HX6	0.971	5	0.001	0.001
9	HX7	0.85	3	0.001	0.001
10	HX8	0.949	3	0.001	0.001
11	He Receiver	-	10	-	-

The results of the simulations for all the three cases are tabulated in the table 4 and compared with modified Claude cycle. In the these simulations, in order to compare the modifications with the Claude cycle, similar Dewar pressure and pressure drops in heat exchangers, are assumed. Hence process compressor suction in case of Claude cycle is at vacuum condition to maintain the Dewar temperature to 4.22 K.

From table 4, it can be seen that Case-1 and Case-3 are better candidates, as refrigeration capacity is increased with a reasonable size and speed of the cold compressor. In Case-2, although the increase in refrigeration capacity is quite large, the speed and diameter of the cold compressor are also high. This size and speed are not practical from stresses and rotor dynamic considerations.

Table 4. Comparison of the results for the three cases with the Claude cycle

Cycle	Total refrigeration at 4.22K (W)	Process compressor Mass flow (g/s)	Mass flow through CC (g/s)	CC Pressure ratio	Size of CC (mm)	Speed of CC (RPM)
Claude	238	39	-	-	No CC	No CC
Case1	283	73	23	1.5	16.3	71,148
Case2	528	80	80	1.7	30.76	3,73,382
Case3	261	80	19	1.55	15.06	76,357

Case-1 is studied further at different temperatures and the results are compared with the basic modified Claude cycle. These simulations seek to bring out the domain temperature zones in which cold compressor based cycles can be employed effectively. Table 5 presents the results of this study.

It can be seen from table 5, that at 5K, the increase in refrigeration capacity of the cycle, even after using the 100% efficient cold compressor, is marginal. Whereas, the increase in refrigeration capacity at 4.22K is considerable. Below 3.8 K the increase in the refrigeration capacity is substantial even with low cold compressor efficiency.

Table 5. Domain of cold compressor applicability

Refrigeration Temperature	Refrigeration Capacity					
	Claude Cycle	Case1 cycle with unit efficiency of CC	Case1 cycle with 65% efficiency of CC	Size of CC efficiency 0.65	Speed of CC (RPM)	Remark
5 K	423.6W	424 W	414W	31.22	2941	not useful
4.22 K	238W	315W	283W	16.3	71,148	Useful
3.8K	91.6W	244W	190W	15.09	1,07,671	Required

4. Conclusions

The following are salient conclusions from the above study:

- A Simulation and optimization tool for cryogenic cycle analysis is developed and validated using reported data.
- 2K hybrid refrigeration cycle similar to the LHC cryogenic cycle has practical difficulties at small/medium scale refrigeration ranges due to requirement of cold compressors that need to operate at very high speeds for good efficiency.
- Cold compressor based modifications to the Claude cycle liquefier proposed as cycle 1 in the present work can be used at small/medium scale refrigeration ranges with speeds of cold compressors in the practical and achievable domains.
- At 5K, the cold compressor based cycle 1 gives comparable performance to the basic pre-cooled Claude cycle only at very high cold compressor efficiencies. This implies that above 5K, cold compressor based cycles similar to cycle 1 do not improve compactness or refrigeration capacity.
- Under the constraint of fixed warm process compressor size (volumetric capacity) as input cold compressor may enhance the refrigeration capacity of the modified Claude cycle refrigerator at

4.22 K even at lower efficiencies at the expense of increased power consumption and reduced COP.

- Below 3.8 K, cold compressor based cycles are highly useful to achieve high refrigeration capacity with a compact system.
- Only single stage cold compressor modifications without sub-atmospheric heat exchangers are studied in this work. With these simplifications, the work demonstrates that the cold compressor technology can be effectively used in small/medium scale helium refrigeration/liquefaction plants to enhance refrigeration/liquefaction capacities.

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