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Dynamic simulation of CHL at SNS

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Abstract. A dynamic simulation model of Central Helium Liquefier (CHL) has been developed by the process simulation software; EcosimPro™. CHL consists of 4 K and 2 K cold boxes to sustain the operation of LINear ACcelerator (LINAC) which is composed of Superconducting Radio Frequency (SRF) cavities installed in the Cryomodules. 4 K cold box is a modified Claude cycle refrigerator, having LN_2 precooler with two Brayton Cycle turbines, followed by the series connected Turbines (Tu3 and Tu4), and a Supercritical Helium (SHe) turbine (Tu5) for high thermodynamic efficiency. The product of 125 g/s of SHe is subcooled at the LHe immersed Heat eXchanger (HX) before supplying to Cryomodules, which has its own precooled HX for He II vapor vs. SHe, to have high liquid yield for He II at 2.1 K. Four series connected Cold Compressors (CCs) keep the LINAC pressure at 0.04 bar for the proton beam acceleration. The paper discusses the modeling of CHL, including four CCs. The benchmark of the model against a design specification of CHL and the validation of CC model is also described in detail.

1. Introduction

SNS cryogenic system is responsible for the operation of LINAC at Oak Ridge National Laboratory (ORNL). It has been demonstrated its high availability, >99 %, for the last 15 years of operation. The system design and procurement were led by Thomas Jefferson National Accelerator Facility (TJNAF) based on their experience with their project. In fact, the design of SNS cryogenic system is approximately 60 % of TJNAF system's capacity with some modification to achieve continuous twenty-four hour, seven-day 2 K operation with a plant availability design goal of 99%[1]. Therefore, the system has been proven to be compliant with the design philosophy.

Table 1 summarizes the major design specifications for CHL; 2.1 K cooling requirements show dynamic/static heat loads due to the beam operation [2]. The nominal design of the CHL is sufficient to cover the dynamic heat loads which are compensated by the embedded heater in each Cryomodule. In principle, CHL operation is considered a steady state; no substantial refrigeration capacity management is required.

Table 1. Summary of CHL capacity/requirement.

Element	Design	Static	Dynamic
2.1 K (kW)	2.4	0.86	0.76
Liquefaction of He I (g/s)	15.0	5.0	2.0
Thermal Shield (kW)	8.5	6.1	-

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2. Dynamic simulation

The dynamic simulation model has been developed for the core of a plant process simulator for CHL, which is considered a versatile tool for process analyses, operator training, online fault diagnostics, verification of new process control before implementing to the real plant. The process simulation captures the complex cryogenic process which can be employed as a virtual plant. Further, the model should be able to contribute machine learning for future cryogenic system development. EcoimPro™has been extensively utilized plant process analyses for LHC and ITER project [4][5][6][7].

3. CHL

Figure 1 shows a simplified Process Flow Diagram (PFD) of a dynamic simulation model consisting of a 4K refrigerator coupled with a 2K cold compressor train pumping on the He II bath, with 7000 L of LHe Dewar (LHD) for the refrigeration capacity management. The thermal shield cooling, represented by the dummy heat load, is provided from the Tu1 outlet and returned to the Medium Pressure (MP) of the Brayton cycle. Further, LINAC is placed as a heat load to the He II bath for the moment, which will be included for the future study. The objective of a simulation is to investigate the cool down process, especially for the CCs pumping down, before reaching the nominal condition for CHL. Note that each Cryomodule has a dedicated 4K-2K HX in the real CHL system, while JLAB has one big HX in the 2K cold box.

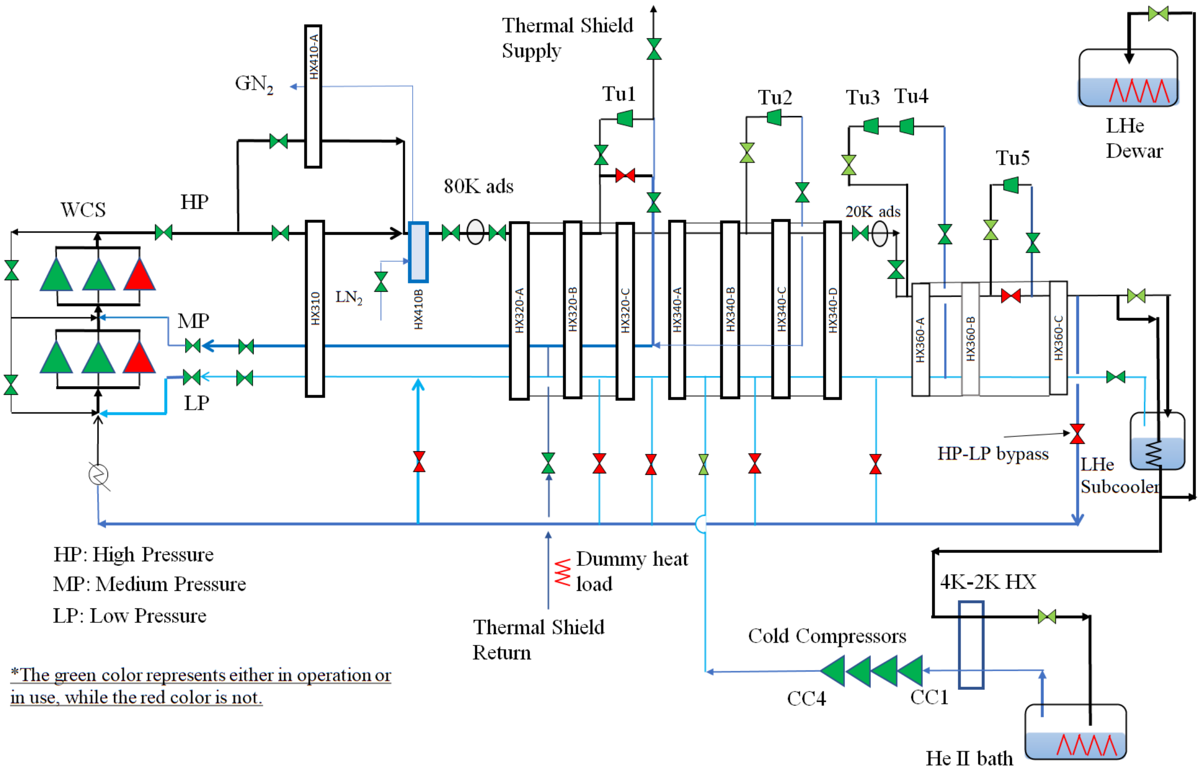

Figure 1. A simplified PFD for the dynamic simulation model for CHL.

3.1. 4K refrigerator modeling

The modeling integrates each component, Warm Compressor Station (WCS), HX, Turbine, Control Valve, and Subcooler, in EcosimPro™, which has been benchmarked against its design specification to confirm its fidelity. Implementation of feedback/sequential controls is required to run the model and bring the refrigerator at its initial condition (300 K at 1 bar) to the nominal state.

3.1.1. WCS model WCS composed from Low Pressure (LP) and High Pressure (HP) stage with 447 kW and 1864 kW oil-flooded Howden 321 screw compressors, respectively. Each stage has three compressor units, however, two units per stage are required for the nominal operation. The design specifies process control settings for three pressure levels; 1.05 bar for LP, 4 bar for MP, and 16.8 bar for HP, associated with the mass-flow rate to the cold box at 1150 g/s. The capacity control of WCS is based on the slide valve positions, implemented in each unit, as monitoring bypass valves, HP to MP & MP to LP, openings.

3.1.2. HX model HXs are designed to combine multiple streams associated with different temperature levels to achieve a high heat transfer rate and compactness. 4K cold box has 3 HX blocks, HX-320/340/360, which must break down each block into different temperature levels, see HX with -A to -D after the tag number, in figure 1. Although the design specification does not include that type of information, it has been arranged for the modeling. Consequently, the 4K refrigerator model is represented by 13 HX modules for the process simulation.

3.1.3. Turbo expander model Linde's turbo-expanders have a gas bearing with a brake circuit to control speed. The modeling is based on the turbine impeller size, and the nominal rotation speed associated with efficiency. Two feedback controls are implemented at the inlet valve to regulate the inlet pressure and turbine power based on the outlet temperature. Meanwhile, the brake circuit controls its rotation speed.

3.2. 2K cold box

The major component of the 2K cold box is four centrifugal-type cold compressors, and the performance curve of each compressor is specified in figure 2, representing the pressure ratio Pr vs the reduced mass flow rate $\dot{m}_r$ as a function of normalized speeds Nr (see equations (1)-(3)). A dotted line represents the surge line, while a dashed line defines the choke condition (equivalent to the conventional centrifugal pump operated at low pressure/temperature regime.). Figure 3 shows the baseline operation setup of CC2-4 with respect to Nr of CC1. If the system follows those Nr lines, the operation points have sufficient margins for surge/choke conditions. Table 2 shows the design specification of the compressor provided by Air Liquide.

$$P_r = \frac{P_{out}}{P_{in}} \tag{1}$$

$$\dot{m}_r = \frac{\dot{m}}{\dot{m}_d}\sqrt{\frac{T_{in}}{T_d}}\frac{P_{in}}{P_{out}} \tag{2}$$

$$N_r = \frac{N}{N_d}\sqrt{\frac{T_{in}}{T_d}} \tag{3}$$

where P is pressure, T is temperature, $\dot{m}$ is mass flow rate, and N is rotation speed. The subscript "in/out" corresponds to the inlet and outlet condition for CC, while d is the design value.

3.2.1. Process control for CCs The process control for the pump-down sequence has been implemented, adjusting rotation speed via Speed Control (SC) based on the He II bath Pressure Control (PC), as shown in figure 4. CC1 control is a primary controller to orchestrate CC2-4 associated with SC2-4. The inlet temperature for CC2-4 is required to calculate the rotation speed during the pump-down process. To ensure the mass flow through CCs, CC4 has a relatively large offset at a low rotation speed. The heater embedded in the He II bath regulates the mass flow through the CC train via Flow Control (FC), imposing the safety margin to the surge condition.

The current operation setup for CHL cold compressors is based on the empirical approach: the pressure is controlled by the heater while the mass flow is regulated by CC4. The simulation model is used to verify the different control approaches for the pumping down process. This is one of the advantages of utilizing process simulation to verify the control logic. In principle, the model with associated control implementation should be able to reproduce the real CC operation [3].

Table 2. Specification of cold compressor.

Category	CC1	CC2	CC3	CC4
Inlet pressure (bar)	0.039	0.109	0.278	0.712
Outlet pressure (bar)	0.113	0.287	0.734	1.300
Inlet temperature (K)	3.978	7.03	11.84	19.60
Outlet temperature (K)	7.0	11.8	19.57	27.03
Nominal speed (Hz)	116	216	409	565

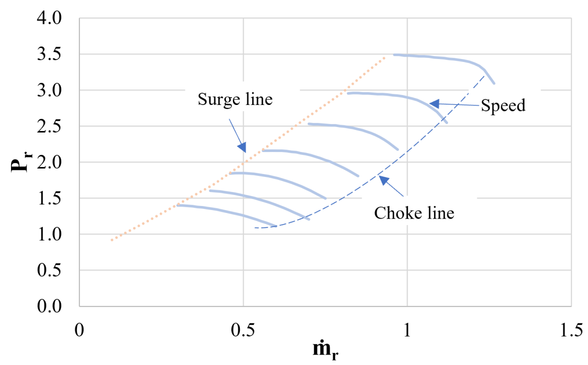

Figure 2. CC1 curve.

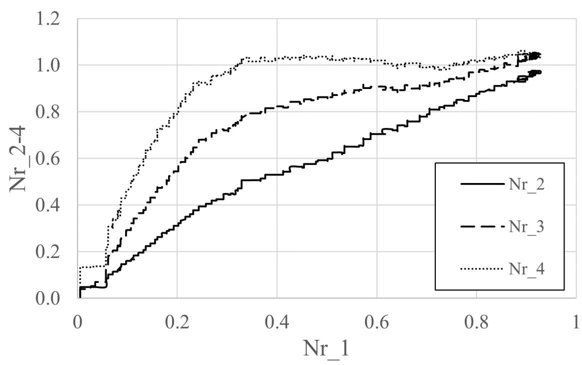

Figure 3. Nr correlation.

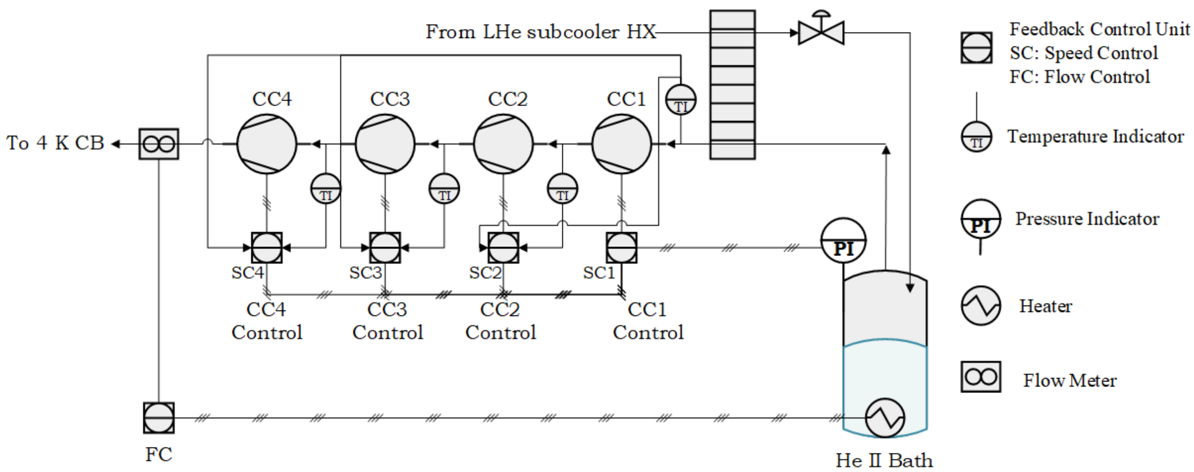

Figure 4. A simplified schematic for the CC process control.

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4. Cool down CHL

4.1. 300-4 K simulation

The sequence of CHL cool down is as follows: first, start WCS and regulate their HP, MP, and LP; second, connect WCS with cold boxes to circulate the flow through HXs; third, start LN_2 precooling circuit to cool down HXs. Meanwhile, the return flow, through the HP-LP bypass, is connected to the LP side of HXs as a function of temperature. Once the cold end of HX310 reaches below 90 K, the cool-down process follows for turbine cooling, starting Tu1 to Tu5 with respect to the cold end temperature. At the onset of Tu5 start, HP-LP & Tu5 bypass valves are closed to accumulate the LHe in the subcooler and He II bath.

Figures 5 through 8 represent the cool-down process simulation results. Figure 5 shows pressure regulation at WCS with their Set Point (SP) as well as Process Values (PV), which reveals well-controlled pressures even though the drastic mass-flow changes due to turbine operations and the CC start-up as indicated in figure 6. Cool-down temperatures, the HP side of HXs, clearly reveal its speed with their slopes, as shown in figure 7. LHe accumulation starts after the Tu5 activation which is the final phase of 4K cool down, as shown in figure 8.

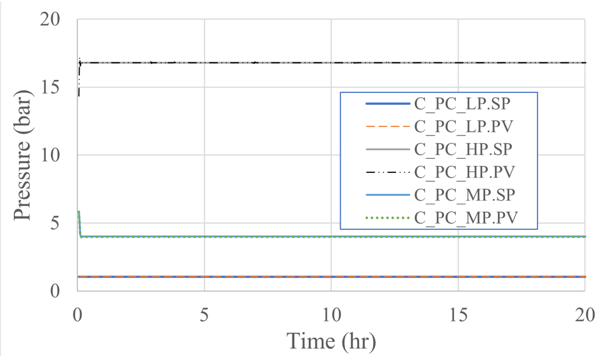


Figure 5. WCS pressure control.

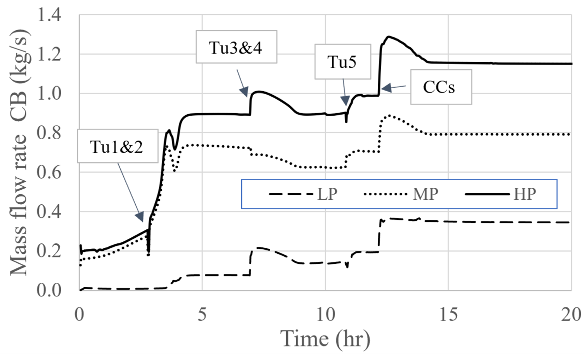


Figure 6. Mass flow variation to the cold box.

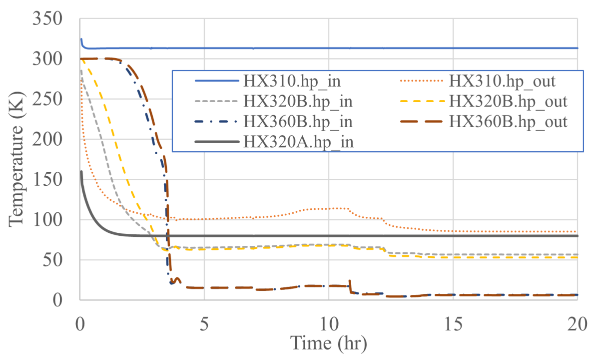


Figure 7. Cool down of HP side.

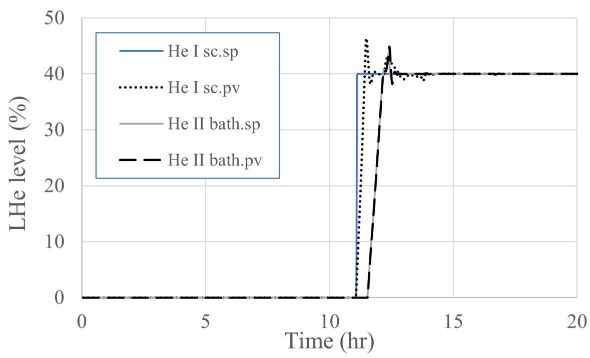


Figure 8. LHe accumulation.

4.2. 4-2K simulation

According to the process control setup, CCs are activated by FC and PC, as shown in figures 9 & 10. FC rapidly ramps up the mass flow rate to ensure sufficient margin to surge conditions, while the CC1 inlet pressure follows gradual SP change based on the real operation. Meanwhile the SPs for the CC's speeds, figure 11, are calculated by utilizing temperatures as shown in figure 12. At the end of pumping down process, the mass flow rate is reduced to the nominal condition to complete the 4 to 2 K cool down.

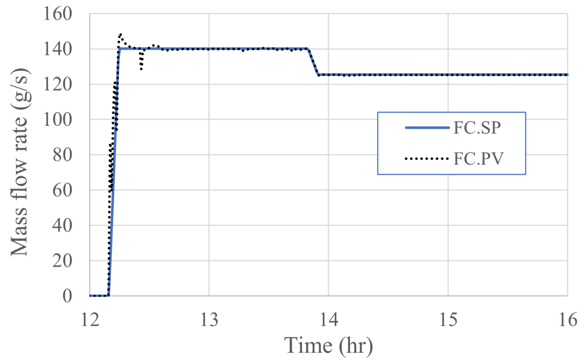


Figure 9. Mass flow control.

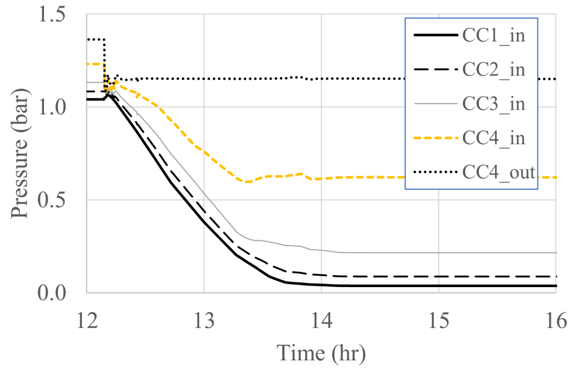


Figure 10. Pressure variation.

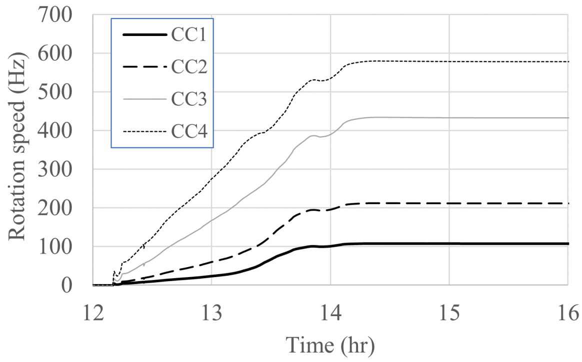


Figure 11. CC speed variation.

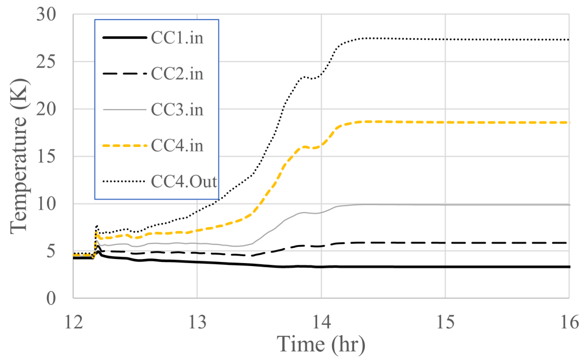
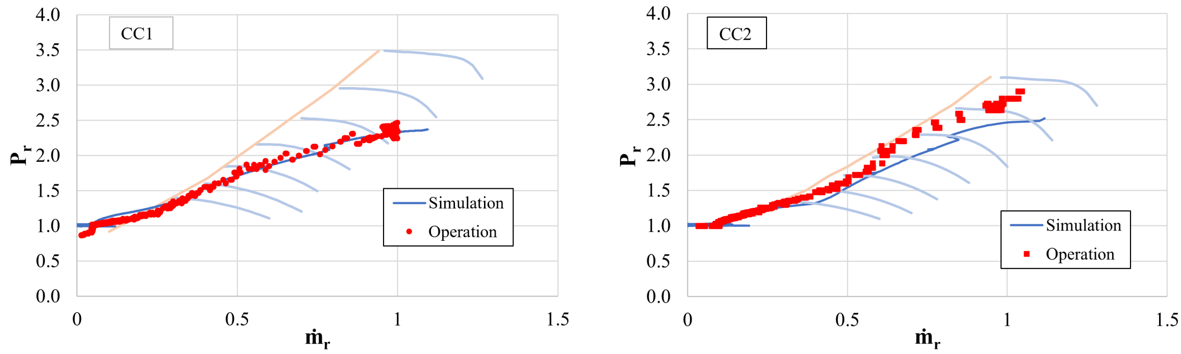


Figure 12. Temperature variation.

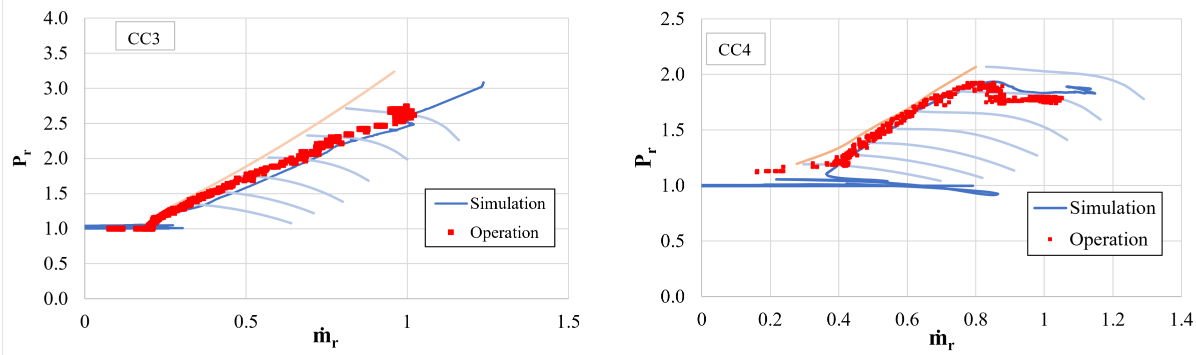
4.3. CC model validation

Figures 13 & 14 compare the simulation results against the real operation. The simulation reproduces trajectory curves well, except CC2. Operation points of CC2 are overlapped on the surge line, while the simulation model represents more margin. Since the re-calibration of pressure/temperature sensors has not been conducted, this might affect the accuracy of PV measurements. This is a common issue for large-scale cryogenic plants as they have difficulty re-calibrating the sensors in situ. In principle, the CC model with associated controls verifies their validity for the 2K cold box upgrade.



(a) (b)

Figure 13. Comparison of operation vs process simulation for CC1(a) & 2(b).



(a) (b)

Figure 14. System operation vs process simulation for CC3(a) & 4(b).

4.4. Benchmark against design specification

The nominal operating condition, under steady state, of the model is compared against the design specification from Linde, as shown in figure 15. Process simulation data points are overlapped on the specification lines, most of the data points are agreed within ±5%, while some process values show ±10% deviations. The model is considered to represent the CHL refrigeration process well to conclude a successful benchmark. To validate the model, the process controls need to be revised for the WCS as well as the cold-end part, utilizing LHD as a refrigeration cycle, to match up with the current CHL operation setup.

5. Exergy analysis

Exergy analysis provides insight into the refrigeration process for a target plant under its nominal state, which is calculated by the following equation.

$$dE = dH - T_0 dS \tag{4}$$

where E is exergy, H is enthalpy, and T_0 is a reference temperature, commonly set at 300 K and S is entropy. Exergy can be evaluated for each component such as HX, Turbo-expander, CC, JT expansion, subcooler, and thermal shield. As setting the reference at the atmospheric pressure and the room temperature (0), it could be appropriate to evaluate the exergy at state x as follows;

$$E_x = \dot{m}\{(H_x - H_0) - T_0(S_x - S_0)\} \tag{5}$$

Thermodynamic efficiency based on the exergy analyses can be expressed as;

$$\eta_{ex} = \frac{\Sigma E_q}{\Sigma E_q + \Sigma EL + \Sigma W_{ET}} = \frac{W_{min}}{W_{act}} \tag{6}$$

where E_q & W_{min} represents the minimum work input for refrigeration/liquefaction, EL is exergy loss and ET is recovered work by turbines, and *act* is for actual work input to the system.

Figure 16 shows the distribution of EL in the system, as one could imagine most of the losses are generated from HXs, while CCs are also contributing a fair portion of losses to the overall system. JT expansion reduces EL due to the precooling before the expansion process, achieving high liquid yield at LHe subcooler as well as He II bath. According to the electric power input for WCS, Carnot work for LN_2 production, and the power input for CCs, the efficiency is approximately 0.17 for the CHL refrigeration cycle.

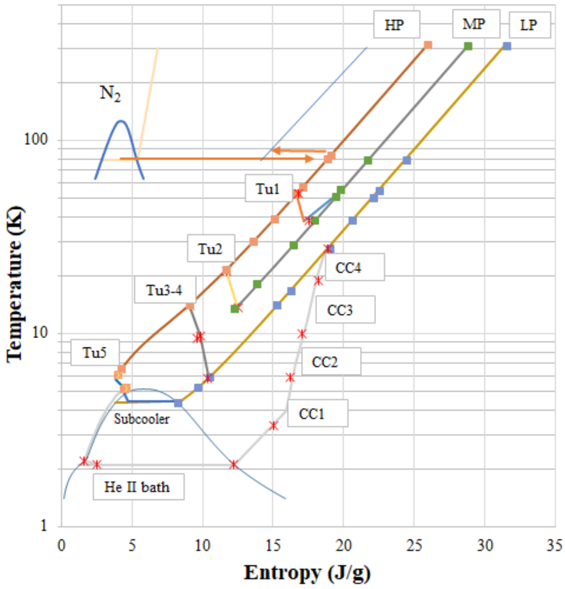


Figure 15. TS diagram.

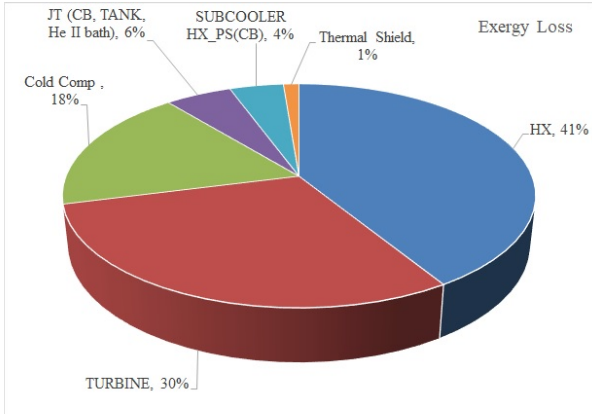


Figure 16. EL distribution.

6. Conclusion

A dynamic process simulation has been performed for CHL at SNS, which showed good agreement with the design specification. The process simulation model, developed by EcosimPro, is considered to benchmark the refrigeration process based on the design values of each component. CCs model validation confirmed the reproducibility of the pumping down process; however, the instrumentation of the 2K cold box needs to be recalibrated to ensure their pumping down trajectory on their performance map. In principle, it has been verified that the model should be able to represent the operating conditions for CCs, which is applicable for the upgrade of a 2K cold box. Validation of the 4K cold box model requires process control revisions at WCS to implement floating discharge pressure to adapt the refrigeration capacity to the demands of LINAC conditions.

7. References

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