Evaluation of Helium Loss for a Closed-loop Cryogenic System

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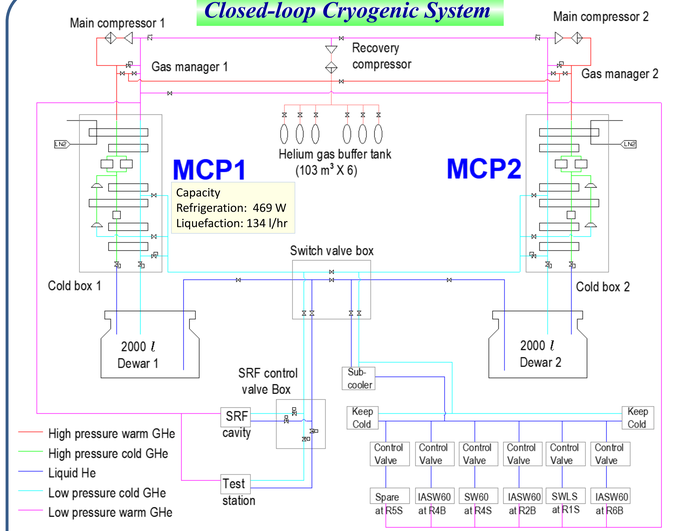
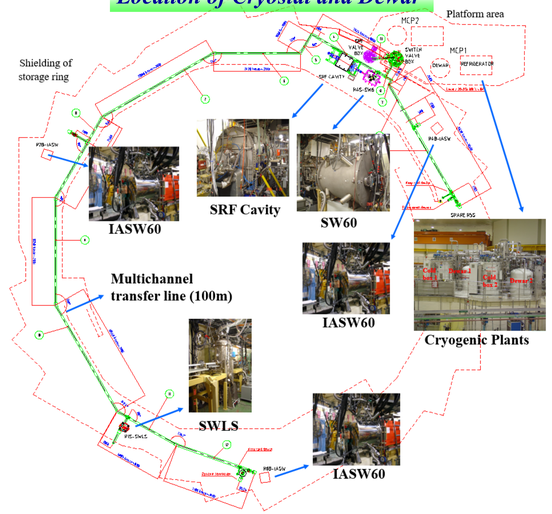
Abstract: Notification of remarkable helium loss in early stage is crucial, especially in the shortage period of helium supply market, for operating a cryogenic plant with its downstream cryostats of superconducting devices. This paper proposes an indicator representing the amount of helium gas remained in the cryogenic plant and associate cryostats during their normal operation period. The indicator is based on normal operation status of the cryogenic system and intakes the effect from outdoors temperature and cryostat geometry. Applying the indicator to retrospect to helium loss from the archived data of an operating cryogenic system shows that the indicator exhibits a peak-to-peak daily variation of up to 1.09% of total amount helium circulated in the system. This indicator is suitable for monitoring the helium loss of a closed-loop cryogenic system being in operation.

Closed-loop Cryogenic System



(1) Separate streams for superconducting radio frequency (SRF) cavity and superconducting magnets (SMs); (2) Refrigeration mode for SRF cavity and liquefaction mode for SMs; (3) Automatic recovery of vaporized helium to the buffer tanks as cryogenic plant (MCP) shutdowns.

Location of Cryostat and Dewar



One superconducting cavity and five superconducting magnets are installed in the storage ring of Taiwan light source (TLS). Two cryogenic plants supply liquid helium required for those superconducting devices.

Approach to simplify analysis

1. Focus on daily normal operation, using helium mass variations as an indicator of loss.
2. Gaseous helium within process components and cryogen helium in transfer lines are considered quasi-stable and are excluded from the indicator.
3. Include warm piping with long length that interconnect the compressor, cold box, and buffer tank. Neglect helium content in short piping sections with small volumes.
4. SM and SRF cavity are fully immersed in a liquid helium bath, eliminating the need to account for their complex geometries when evaluating helium inventory.

Calculation equation

$$HS = \sum_i (V_{s,i}),\ i \in \{\text{buffer tank, warm piping, cryostat, dewar}\}$$

Buffer tank: $V_s = \frac{T_s}{T} \times \frac{P}{P_s} \times V_{tank}$

Warm piping: $V_s = \frac{P}{P_s} \times L_{pipe} \times A_{pipe}$

Dewar: $V_s = V_{dewar} \times \{H \times \rho^l_{T,dewar} + (1-H) \times \rho^g_{T,dewar}\} / \rho_s$

SRF cavity: $V_s = V_{SRF} \times \{H \times \rho^l_{T,SRF} + (1-H) \times \rho^g_{T,SRF}\} / \rho_s$

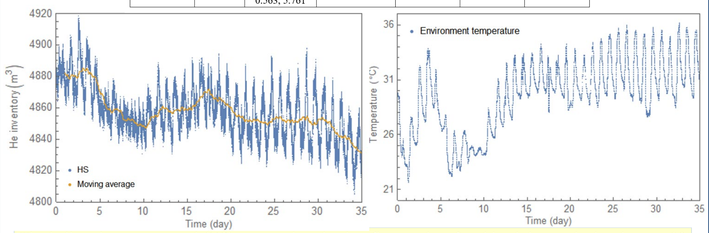
Superconducting magnet: $V_s = V_{SM} \times \{H \times \rho^l_{T,SM} + (1-H) \times \rho^g_{T,SM}\} / \rho_s$

V: volume; H: level; g: gas phase; ρ: density
T: temperature; L: length; l: liquid phase; HS: He inventory
P: pressure; A: area; s: reference state

Initial result of total helium in cryogenic system

Parameters used for evaluation of total helium in TLS cryogenic system

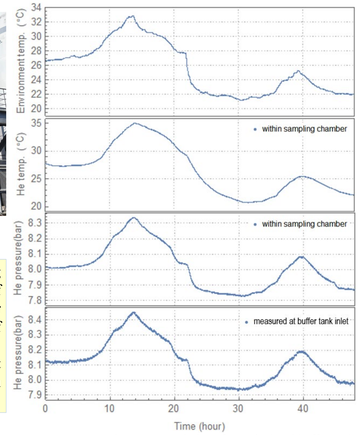
Item	Quantity	Volume (m^3)	Density (kg/m^3)	Pressure (bar)	Temperature (K)	Level (%)
Reference state	–	–	0.16252	1.01325 (1 atm)	300	–
Buffer tank	6	(Horizontal) 103.0	–	measured	environment	–
Dewar	2	(Vertical) 2.0	liquid: 116.646 gas: 24.176	1.40	4.587	measured
SM	5	(Vertical) 0.04 (Horizontal) 0.25, 0.121, 0.121, 0.121	liquid: 123.728 gas: 17.977	1.07558 (15.6 psi)	4.288	measured
SRF	1	(Horizontal) 0.5	liquid: 119.687 gas: 21.448	1.26312 (18.32 psi)	4.467	measured
Long piping	6	0.313, 0.563, 5.761, 0.8, 0.563, 5.761	–	measured	–	–



The helium inventory trend (HS) was analyzed using five weeks of archived data, calculated every 30 seconds, displayed with a one-day moving average window. HS is significantly influenced by environmental temperature, with daily variations ranging from 60 to 72 m³ (1.23% to 1.49% of the daily average) on days with substantial temperature fluctuations.

Refine the evaluation of helium inventory to reduce variation of HS

Temperature difference for the buffer tanks at various locations



Temperature and pressure variations for an isolated buffer tank.

(1) A small, thermally insulated sampling chamber is attached to the non-inlet side of each tank. Sensors inside the chamber monitor the temperature and pressure of the helium gas within the buffer tank.
(2) Account for temperature differences at various locations and the time lag between pressure and temperature changes.

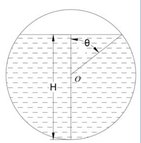
SM cryostat with horizontally positioned cylindrical vessel

$$V_s = V_{SM} \times \{V_f \times \rho^l_{T,SM} + (1 - V_f) \times \rho^g_{T,SM}\} / \rho_s$$

where

$$V_f = 1 - \{\theta - (2H-1) \times \sin(\theta)\} / \pi$$

$$\theta = \cos^{-1}(2H-1) \ \text{ and } \ H \geq 50\%$$



Neglecting the geometry effect of a horizontally positioned cryostat will lead to an underestimation of the helium inventory for liquid helium level above 50%. SM cryostat does not have continuous liquid helium flow, and its level fluctuates between maximum and minimum values. A volume factor V_f is introduced to account for both geometry and liquid helium level.

Non-uniform temperature of cold helium gas in cryostat and dewar

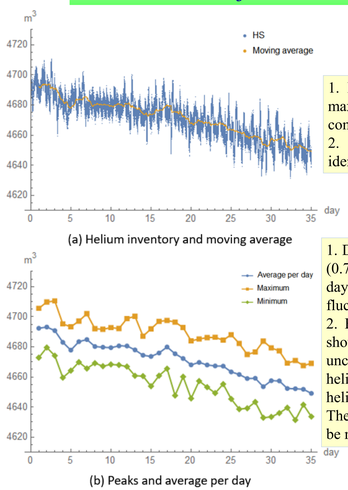
$$\rho^g_{T,SRF} \Rightarrow F \times \rho^{g(saturation)}_{T,SRF}$$

$$\rho^g_{T,SM} \Rightarrow F \times \rho^{g(saturation)}_{T,SM}$$

$$\rho^g_{T,dewar} \Rightarrow F \times \rho^{g(saturation)}_{T,dewar}$$

Cold helium gas above the liquid level contains a temperature gradient. Using the saturation temperature density to calculate the gas weight tends to overestimate the inventory. A factor F of 0.5 is chosen to adjust the saturation gas density.

Total helium in TLS cryogenic system after refined evaluation

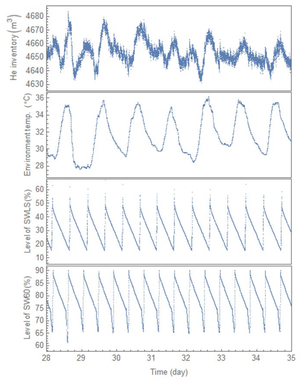


(a) Helium inventory and moving average

(b) Peaks and average per day

1. Deviation between the envelopes of maximum and minimum peaks is smaller comparing to the initial result.
2. Moving average more effectively identifies helium inventory loss.

1. Daily variation ranges from 36 to 51 m³ (0.76% to 1.09% of the daily average) on days with great environmental temperature fluctuations.
2. From days 4 to 17, the daily average shows negligible helium loss, with an uncertainty of ±6 m³ (±0.13% of total helium). From days 17 to 35, the average helium loss is 1.7 m³ (0.28 kg) per day. These results suggest that helium loss can be reliably monitored on a weekly basis.



1. Peak values are primarily caused by sudden environmental temperature changes and sharp fluctuations in level readings during the filling of liquid helium into the SWLS and SW60 cryostats.
2. Environmental temperature change dominates the variation in HS, despite the calculation equation accounting for the temperature of helium gas in the buffer tanks.

Summary

1. An indicator HS for monitoring the variation in total helium inventory within the cryogenic system under normal operating conditions has been developed. It accounts for temperature differences in the buffer tanks, the geometric effects of horizontally positioned cryostats, and the non-uniform temperature of cold helium gas in the cryostat and dewar.
2. Verification using five weeks of archived data shows that this indicator exhibits a peak-to-peak daily variation of up to 1.09% of the total helium inventory, with a daily average uncertainty of ±0.13%..
3. This indicator is suitable for real-time monitoring of helium inventory, allowing for weekly identification of helium loss and early detection of system leakage..