Development of a moisture removal device for helium cryogenic plants

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Abstract. Water contamination represents a critical challenge in helium cryogenic systems, presenting multifaceted operational risks for advanced industrial and scientific facilities. These water contaminants undergo complex phase transformations during system operations, crystallizing under extreme low-temperature conditions and posing significant threats to precision engineering infrastructure. Such crystallized particles can critically damage sensitive mechanical components, particularly turbines within coldbox assemblies, and accumulate within intricate heat exchanger networks, progressively compromising thermal transfer efficiency and overall system performance. At the National Synchrotron Radiation Research Center (NSRRC), we have developed an innovative moisture removal device capable of eliminating water contaminants both during offline maintenance and online system operation. Currently, four of these devices are deployed: one at the Taiwan Photon Source (TPS), two at the Taiwan Light Source, and one integrated with the purification system to enhance moisture contaminant removal capabilities. This paper will detail the device's design and present comprehensive testing results.

KEYWORDS: Cryogenics; Moisture contamination; Moisture adsorption; Molecular sieve; Aluminum oxide; Helium; Liquefier; Refrigerator.

1. Introduction

The National Synchrotron Radiation Research Center (NSRRC) operates helium cryogenic systems at both the Taiwan Light Source (TLS) and Taiwan Photon Source (TPS) to cool superconducting devices in the electron storage rings [1-4]. These systems consist of a compressor station that pressurizes helium gas, which is then cooled into liquid form in the liquefier/cold box. This unit, containing heat exchangers, expansion turbines, and a throttling valve, reduces the helium to low pressure and stores it in a dewar. The liquid helium is transferred through vacuum-insulated piping to the superconducting magnets or cavities, maintaining the required cryogenic temperatures. As heat generated by the superconducting devices is rejected to the liquid helium, the helium absorbs this heat, vaporizes, and is returned to the liquefier where it is mixed with cold helium gas from the dewar. This gas exchanges heat with the incoming warm helium before being re-pressurized.

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Over time, moisture from various sources accumulates in the low-temperature heat exchanger, solidifying and causing operational issues. A common effect is a pressure drop across the heat exchanger, reducing liquefier efficiency. In severe cases, moisture may damage critical components like the expansion turbine. Moisture contamination arises from leaks, overpressure events triggering safety valves, maintenance activities, and residual moisture in the cooling oil after maintenance. Such contamination poses a significant challenge for cryogenic plants in light sources that require long-term, high-reliability operation.

2. Efficient moisture removal in helium liquefiers using partial-flow modules for enhanced cryogenic system performance

Moisture removal in helium liquefiers is traditionally achieved by either warming the entire liquefier or focusing on the first heat exchanger [5, 6]. In the first method, the liquefier is heated above the melting point of ice, allowing water to be drained through a port using pressurized helium gas or a vacuum pump, followed by several pump-and-purge cycles with pure helium. Alternatively, room-temperature helium gas can be cycled through the first heat exchanger, with a filter cartridge used to adsorb the moisture. Both methods require several days and must be performed during the liquefier shutdown.

The liquefiers at TPS and TLS are supplied by different manufacturers, leading to different maintenance protocols. TPS uses the vacuum pump-based method, while TLS uses the filter cartridge approach. Warming the superconducting cavity to room temperature presents challenges, such as the risk of vacuum seal failure due to thermal stress during the temperature cycle. A past failure of this kind caused significant operational disruption, highlighting the risks of such thermal cycling. Furthermore, the process of warming and cooling the cavity is time-consuming, often taking weeks, which underscores the importance of avoiding unnecessary thermal cycles. To mitigate these risks, both TLS and TPS strive to maintain the cavities at cryogenic temperatures whenever possible, ensuring higher accelerator availability and uninterrupted experiments.

At TLS, moisture removal can be managed during shutdown due to the presence of two liquefiers. However, TPS has only one liquefier, limiting the time available for moisture removal. The planned addition of a third superconducting cavity at TPS will further reduce available downtime due to increased cryogenic demand. These challenges require the development of a more efficient moisture removal method. To address this, we implemented smaller, partial-flow moisture-removal modules instead of a full-flow system that would require extended shutdowns. A full-flow module treats the entire helium circulation stream and is installed in-line before the liquefier, which requires the cryogenic system to be fully shut down for installation, maintenance, or regeneration. Although such an approach could be feasible if three full-flow isolation valves were installed from the beginning, it inevitably disrupts operation for extended periods. In contrast, partial-flow modules divert only a fraction of the helium stream through the adsorbent bed at selected points (liquefier, compressor station, recovery line). This design allows continuous operation of the main cryogenic loop while still achieving effective moisture removal, an advantage particularly critical for facilities such as TPS that operate with only a single liquefier. These modules are strategically placed at critical locations, capturing moisture without disrupting system performance. The liquefier module captures moisture during the heat exchanger warming phase, the compressor station module removes moisture introduced by new cooling oil or charcoal during start-up, and the helium recovery module prevents moisture from the compressor or helium return flow from entering the buffer tanks. All new charcoal was

thermally baked before installation to minimize residual moisture release. Regarding oil, the compressor skid of the older system was equipped with standard oil-removal elements, including filters and coalescers, but these were not always sufficient to completely prevent oil-associated moisture from migrating into the helium loop. The addition of the moisture-removal modules therefore provides an essential safeguard, ensuring system reliability and stable liquefier performance. Figure 1 illustrates the flow diagram of this system.

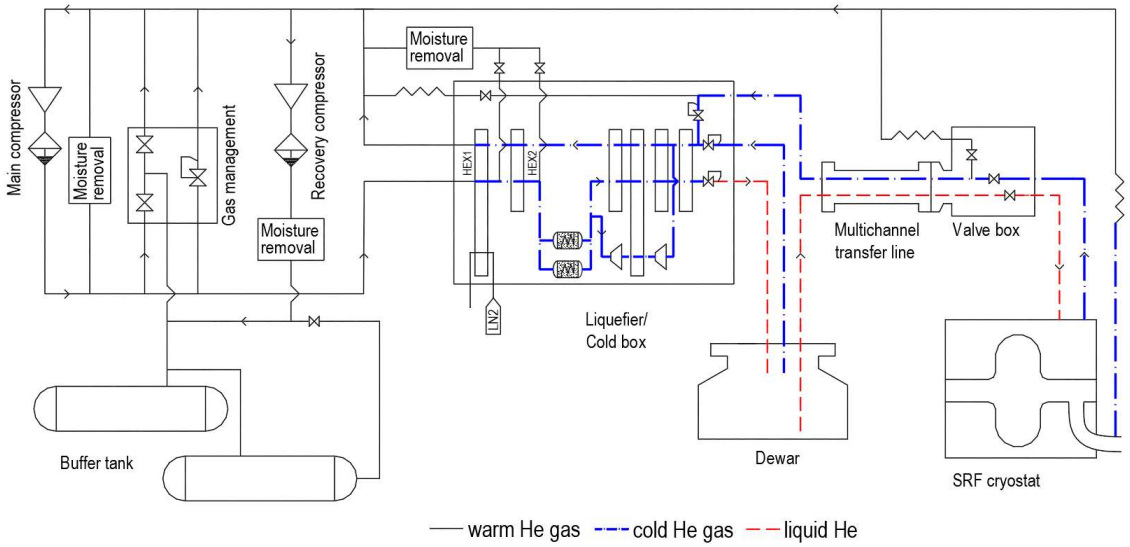

Figure 1. Cryogenic system incorporating partial-flow moisture removal devices [7].

3. Design and implementation of moisture-removal devices for enhanced helium liquefier performance

Effective moisture removal from helium gas is essential for maintaining stable operation in cryogenic plants. In this work, a dual-layer adsorbent vessel was developed and deployed as a Moisture Removal Device (MRD), as shown in figure 2. The lower half of the vessel is filled with aluminum oxide (Al_2O_3), while the upper half contains molecular sieves. Helium gas enters from the bottom, first contacting the activated alumina layer, which has a large surface area and strong affinity for water vapor, providing high initial uptake. The partially dried gas then passes through the molecular sieve layer, where residual moisture is selectively adsorbed. The dried helium exits from the top outlet, ensuring the required level of dryness for cryogenic plant operation.

For this study, BASF F-200 activated alumina (spherical beads, diameter 4.7 mm [8]) and UOP 13X-APG molecular sieves (beads, diameter 4 mm [9]) were selected for their superior adsorption properties. A plenum chamber located beneath the alumina bed regulates flow distribution, minimizing turbulence and ensuring uniform contact between the helium and the adsorbents. To contain the materials, three layers of 40-mesh stainless steel wire cloth are installed, while a downstream 0.1-μm filter prevents fine particles from entering the cryogenic system as shown in figure 3.

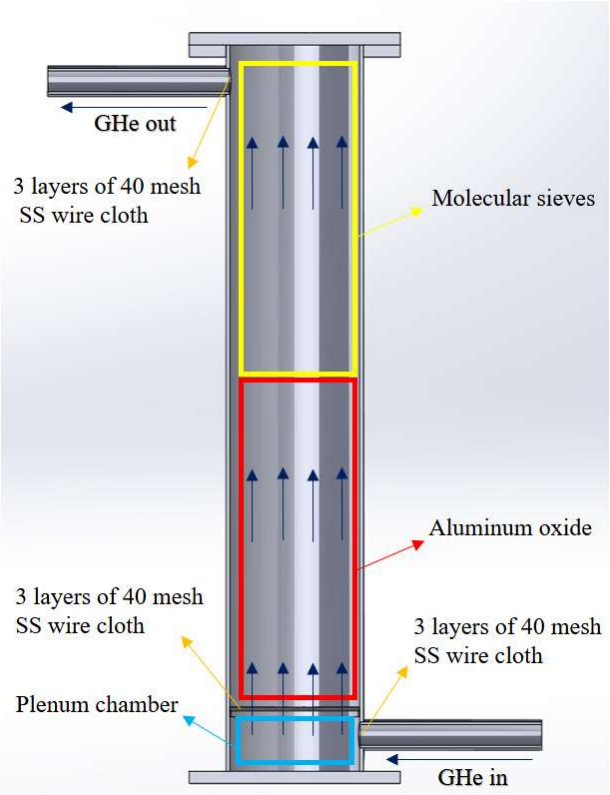

Figure 2. Design of moisture-removal device [7].

Figure 3. A 0.1-micron filter downstream of the moisture-removal device.

Compared with standard commercial moisture traps, the MRD is specifically designed for integration into helium cryogenic plants. Its dual-layer adsorbent bed provides both high initial capture and deep drying capacity, while the partial-flow configuration enables installation at critical points—liquefier, compressor station, and recovery line—without requiring full system shutdowns. In practice, each MRD operates at helium pressures of 2–10 bar and ambient temperature (~293 K), handling partial flow rates corresponding to 10–20% of the main circulation stream. Under these conditions, the MRD reliably reduced moisture concentration from ppm levels to below 0.5 ppm during validation tests. These tailored design features make the MRD more compatible and effective for large-scale cryogenic helium systems than conventional commercial cartridges.

4. Performance validation of the moisture removal device in a closed-loop helium cryogenic system

Building upon the design and implementation described in the previous section, we next evaluate the performance of the Moisture Removal Device in a closed-loop helium circulation system. The MRD, introduced in Chapter 2 as a dual-layer adsorbent module, was strategically installed at the compressor station, gas tank, and cold box. Its effectiveness was assessed by monitoring moisture concentration at these critical locations, and the following results demonstrate its ability to maintain system dryness and operational stability.

4.1 Experimental setup

The helium cryogenic plant employs a closed-loop helium gas circulation system driven by a helium compressor. This setup ensures continuous gas flow through the MRD units. To evaluate the performance of the MRD, three identical devices were placed at different locations throughout the system:

1. Compressor Side
2. Gas Tank Side
3. TPS Cold Box (CB) Side

Moisture sensors were installed at the inlet of each MRD unit to measure the water vapor content in the helium stream before treatment. The data presented in this section originates from these measurement points and illustrates the consistency and effectiveness of moisture removal across the system. The primary moisture sensor used was Linde's Multi-Component Detector (WE34DM-3/SM38), with verification by Alpha Moisture Systems' AMT-RED analyzer to ensure accuracy and redundancy.

4.2 Results and discussion

Although systematic baseline data were limited during the early operation of the original system, comparative measurements obtained during compressor restart phases provided clear evidence of the benefit of the moisture-removal modules. Without modules, outlet moisture concentrations typically increased to 3–4 ppm or higher, whereas with dual-layer modules the concentration rise was restricted to less than 0.5 ppm. This historical comparison highlights the significant effectiveness of the MRD in reducing moisture accumulation. For future studies, standardized pre-installation measurements at the compressor, gas tank, and cold box locations will be implemented to enable more direct comparisons of moisture concentration before and after MRD installation.

4.2.1 Moisture concentration at the compressor side

The moisture concentration data at the inlet of the MRD placed on the compressor side is presented in figure 4. The results indicate that the incoming helium at this location initially exhibited relatively high moisture content due to the proximity to mechanical operations and ambient interfaces. Following the installation of the MRD, a notable decrease in inlet moisture concentration was observed over time, demonstrating the system's ability to maintain dry conditions even at this mechanically active point.

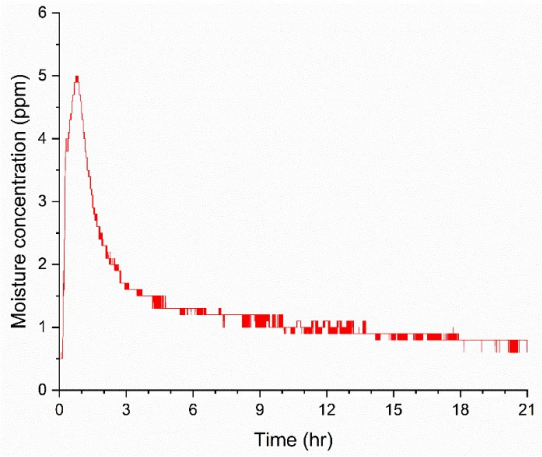

Figure 4. Moisture concentration at the inlet of MRD - Compressor Side

4.2.2 Moisture concentration at the gas tank side

As shown in figure 5, the MRD located on the gas tank side also encountered moderate moisture levels at its inlet. The gas tank, serving as a buffer reservoir, tends to accumulate minor impurities, including moisture. The measurements confirm that the MRD at this location effectively handles this residual moisture, thereby maintaining the helium gas quality throughout the storage phase of the circulation loop.

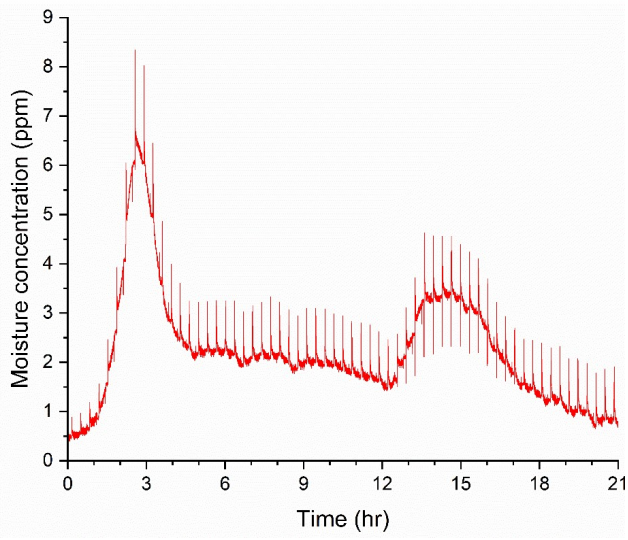

Figure 5. Moisture concentration at the inlet of MRD - Gas Tank Side

4.2.3 Moisture concentration at the TPS cold box side

The TPS Cold Box (CB) side represents a critical location where helium is utilized at cryogenic temperatures. As indicated in figure 6, moisture content at this point was minimal, reflecting both the effectiveness of upstream MRDs and the importance of maintaining dryness in cryogenic zones. The low inlet moisture concentration also confirms the integrity of the closed-loop design and validates the placement strategy for MRDs within the system.

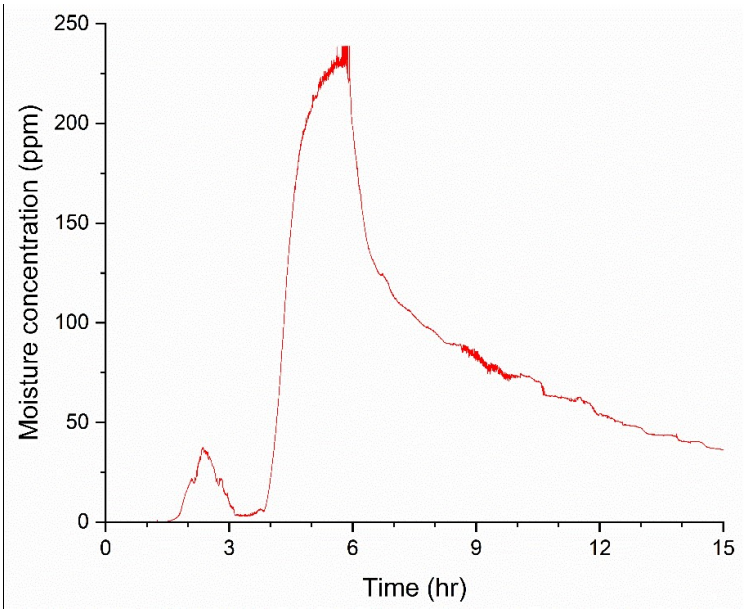

Figure 6. Moisture concentration at the inlet of MRD - TPS CB Side

5. Conclusion

The deployment of Moisture Removal Devices in key locations within the helium circulation loop has proven effective in reducing and maintaining low moisture concentrations throughout the system. The closed-loop operation, reinforced by strategic MRD placement and continuous helium circulation via a compressor, ensures that moisture ingress is managed efficiently. The results validate the design and practical implementation of the MRD for use in helium cryogenic plants, highlighting its potential for broader applications in ultra-clean gas systems.

Acknowledgments

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