# Design and Fabrication of a 4 K Helium Phase Separator

Liquid helium (LHe) is transported from the cryogenic system to superconducting devices through multi-channel transfer lines. However, unavoidable heat loss during transmission causes the LHe to transition into a two-phase flow, which can significantly impact the performance of cryostats in superconducting or other devices not continuously filled with LHe. Helium phase separators were developed at the NSRRC to re-condense the two-phase helium flow from a liquid-helium transfer line and ensure a stable supply of LHe to users.[1,2]

A G-M cryocooler (Sumitomo, model RDK415D) with a cooling capacity of 1.5 W at 4.2 K was integrated into the phase separator to re-condense and liquefy helium while storing it in a 100 L vessel. Practical improvements to reduce the heat load on the helium phase separator were also discussed and implemented.

**Figure 1** depicts the configuration of the helium phase separator.[3,4] The second-stage cold head of the cryocooler, which provides a maximum cooling capacity of 1.5 W at 4.2 K, is connected to an oxygen-free copper condenser mounted at the top of the 100 L LHe vessel. To minimize heat transfer through radiation and convection, the LHe vessel is wrapped in multi-layer insulation (MLI) and housed within a vacuum vessel.

The vessel is supported by four G-10 fiberglass-epoxy rods installed at its base, with the opposite ends secured to the outer vessel to bear the weight of the LHe. Three transfer pipes at the top of the vessel act as inlets and outlets for LHe and as a vent for gaseous helium. Vacuum barriers are placed between the transfer pipes and the outer vessel to mitigate conductive heat loss from room temperature.

A thermal shield made of 30 layers of MLI is connected to the first-stage cold head of the 4 K cryocooler. Positioned between the outer vessel and the LHe vessel, this shield blocks radiative heat loss. Additionally, a thermal bridge made of copper connects the thermal shield to the cryogenic valves, further reducing conductive heat loss. The thermal shield and bridge are constructed of copper, while the outer vessel, LHe vessel, and transfer pipes are made of stainless steel, ensuring durability and effective thermal isolation.

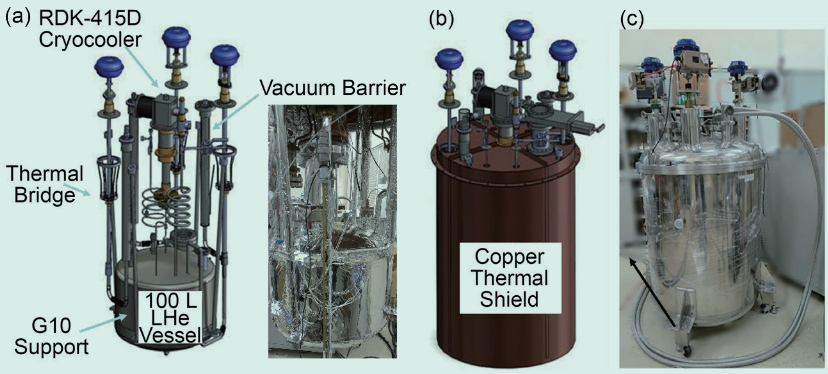


**Fig. 1**: Configuration of the helium phase separator. (a) Components after removal of the thermal shield; (b) outer vessel removed to reveal the thermal shield; (c) prototype of the helium phase separator. [Reproduced from Ref. 3]

**Figure 2** illustrates the piping and instrumentation diagram of the helium phase separator, outlining its operational process. In the first step, the thermal shield was cooled to below 80 K using the first-stage cold head of the cryocooler. Helium gas from the bundle entered the LHe vessel through the pre-cooler, where its temperature was initially reduced. Further cooling occurred *via* heat exchange in the condenser, which was thermally connected to the second-stage cold head of the cryocooler, which brought the helium to its liquefaction temperature.

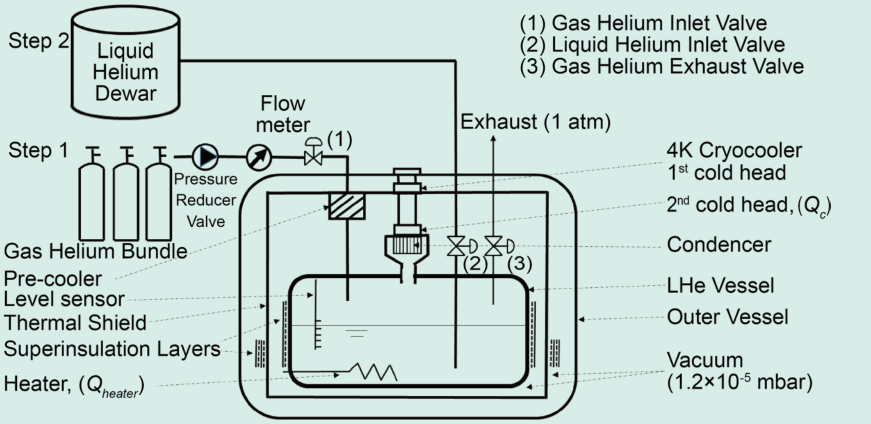


**Fig. 2**: Configuration of the experiment. Step 1: the separator was cooled with the cryocooler. Step 2: the LHe vessel was filled with LHe; the inner heater was then activated to ensure stable operation in this closed system. [Reproduced from Ref. 3]

The pressure in the LHe vessel was maintained at approximately 1.67 bar-a, and key temperatures, including those of the thermal shield, LHe vessel, condenser, and cold head, were monitored. This was done to confirm that the condenser temperature had reached or dropped below the helium liquefaction temperature of 4.8 K at 1.67 bar-a. Achieving this condition ensured helium liquefaction and confirmed that the separator's heat load was within the cryocooler's cooling capacity. This step established the initial cooling and liquefaction process critical for the subsequent liquid-helium operations.

In the second step, LHe was transferred from the dewar to the LHe vessel under the established operating conditions. During the transfer, a portion of the LHe was naturally consumed and vented to the atmosphere through the exhaust valve, which remained open to allow for pressure regulation.

Once the desired operating level of LHe in the LHe vessel was reached, all inlet and exhaust valves were closed, converting the system into a closed configuration. To maintain stable operating conditions, a heater installed in the LHe vessel was activated. The heater's power was precisely adjusted to stabilize both the LHe level and the internal pressure of the vessel. This heating power played a critical role in determining the overall heat load of the system, providing the valuable data for evaluating the thermal performance and efficiency of the helium phase separator.

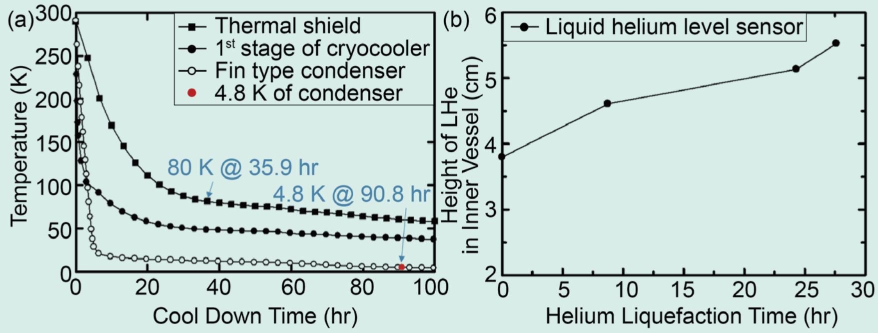


**Fig. 3**: Experimental results. (a) Cooling-down curve; (b) helium liquefaction rate. [Reproduced from Ref. 3]

**Table 1**: Thermal parameters.

| m | $T_e$ | $h_e$ | $T_1$ | $h_1$ | $Q_1$ | $h_{2G}$ | $h_{2L}$ | $Q_S$ | $Q_L$ | $Q_{2nd}$ | $Q_{1st}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (g/s) | (K) | (J/g) | (K) | (J/g) | (W) | (J/g) | (J/g) | (W) | (W) | (W) | (W) |
| 0.0026 | 295 | 1532 | 54 | 281 | 3.25 | 14.06 | -1.34 | 0.69 | 0.04 | 0.73 | 13.8 |

Helium liquefaction: **Figure 3(a)** illustrates the cooling process of the helium phase separator. The temperature of the thermal shield dropped below 80 K after approximately 35.9 hours. The condenser temperature reached the liquefaction point of 4.8 K at 1.67 bar-a after approximately 90.8 hours, as indicated by the red point in **Fig. 3(a)**. This marked the initiation of the helium liquefaction process. **Figure 3(b)** shows the measured helium liquefaction rate, which was approximately 1.4 cm/day, equivalent to approximately 1.8 L/day. The associated thermal parameters were calculated based on data obtained from the *Helium Material Handbook* and relevant thermodynamic principles, as summarized in **Table 1**. These data provide insights into the thermal efficiency and performance of the separator during its operational cycle.

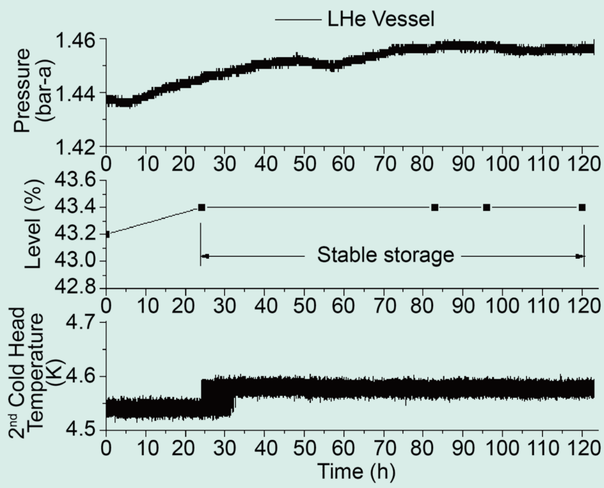


**Fig. 4**: LHe filling and stable storage. [Reproduced from Ref. 3]

LHe storage: **Figure 4** illustrates the storage process of LHe. The LHe level was maintained at 43.4% by activating the internal heater, which was operated at a power of 0.337 W. The internal pressure was stabilized at 1.46 bar-a ± 0.015 bar throughout the storage period. During this process, the condenser effectively re-condensed the

**Table 2**: Experimental measurements.

| $Q_{heat}$ (W) | LHe vessel pressure (bar-a) | Level (%) | First cold-head temperature (K) | Second cold-head temperature (K) | $Q_c$ (W) | $Q_{load}$ (W) |
|---|---|---|---|---|---|---|
| 0.337 | 1.46 | 43.4 | 35.6 | 4.59 | 1.892 | 1.555 |

vaporized helium, maintaining a steady state. This stability was sustained for a duration of 96 hours, demonstrating that the heat load of the separator was consistently below the cooling capacity of the cryocooler. This ensured efficient and reliable operation of the helium phase separator during the storage phase.

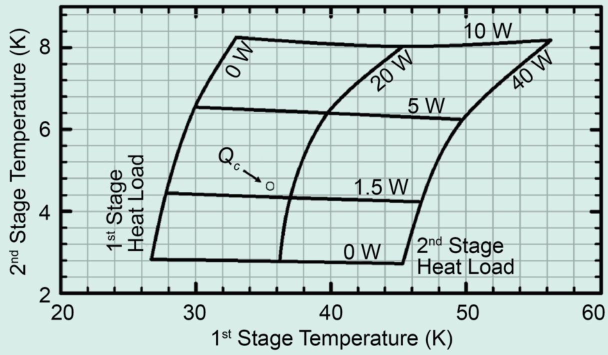


**Fig. 5**: RDK-415D cold-head load map (60 Hz). [Reproduced from Ref. 5]

The experimental data are summarized in **Table 2**. The results indicate that the cooling capacity of the second-stage cold head ($Q_c$) was approximately 1.892 W,[5] as derived from the cryocooler load map shown in **Fig. 5**. The electrical power of the heater ($Q_{heat}$) was measured to be 0.337 W. Using the equation $Q_{load} = Q_c - Q_{heat}$ , we calculated the heat load of the LHe vessel $Q_{load}$ , to be 1.555 W. This analysis highlights the effectiveness of the cryocooler in maintaining thermal stability while accounting for the heat input from the heater.

During the transmission process, LHe was prone to vaporization due to the heat, leading to the formation of a two-phase fluid within the transmission pipeline. This phenomenon significantly reduced transmission efficiency, hampering the delivery of sufficient LHe and causing instability in user systems.

To address this challenge, the cryogenics group developed a cryogenic freezer re-condensing LHe phase separator. The primary function of this system was to re-condense the two-phase fluid in the pipeline and re-liquefy the separated low-temperature helium gas. The output from the phase separator was high-purity LHe, which effectively minimized the dryness of the LHe in the transmission pipeline, improving the overall stability of the cryogenics system.

The successfully developed re-condensation LHe phase separator could be coupled with a 4 K cryogenic cryocooler to enable zero-boiling operations to condense low-temperature helium. The special design of the radiation isolation baffle further reduced the heat load. In addition to condensing low-temperature helium and storing LHe, the system could convert normal-temperature helium (295 K) into LHe (4 K), functioning as a small-scale liquid-helium production machine.

The system's net cooling capacity was approximately 0.337 W at 4.59 K, with a LHe production rate of approximately 1.8 L per day. The total heat loss was measured at approximately 1.555 W at 4.59 K, showcasing the system's efficient performance. (Reported by Wen-Rong Liao and Chin-Kang Yang)

## References


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