A Separated two stage helium liquefier using a 4 K GM cryocooler

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Abstract. A small-scale helium liquefier using a GM cryocooler (1.5 W @ 4.2 K) is designed and built. The helium gas to be liquefied is precooled by the cryocooler with natural convention loop and the precooling process inside the liquefier is separated to two stages by the first stage cold head of the cryocooler. Liquid nitrogen is used for cooling helium gas before entering the liquefier and cooling the radiation shield as well. The liquefier can start producing liquid helium within 7.5 hours after running from room temperature. A liquefaction rate of 18.57 L/day is obtained at a working pressure of about 115 kPa. Simply designed with high performance makes this helium liquefier appropriate to be used directly with cryostats for scientific experiments of liquid helium temperature range.

1. Introduction

Liquid helium has bridged the gap between the physics and ultra-low temperature (below 10 K), and promoted the development of science and technology greatly. Small scale helium liquefier is being largely required as a flexible and convenient liquid helium supporting solution.

Since the 4 K cryocooler was developed in the end of last century, both the Gifford-McMahon (GM) cryocooler and the pulse tube (PT) cryocooler have successfully liquefied helium without the use of a Joule-Thomson stage [1], [2]. Because of these 4 K cryocoolers had simple structure, good stability and high reliability, making them widely used in small scale helium liquefaction systems and developed rapidly. In previous reports, the PT cryocooler with a cooling capacity of 1.5 W at 4.2 K got a liquefaction rate of 20 L/day (C. Wang, 2009) [3], and a liquefaction rate of 13 L/day was obtained by using a GM cryocooler with 1.5 W cooling power at 4.2 K (P. Schmidt-Wellenburg, 2006) [4].

In this paper, a small-scale helium liquefier is built based on a 1.5 W @ 4.2 K GM cryocooler (Sumitomo model RDK415). Inside the liquefier, helium gas is cooled by the GM cryocooler through a closed-cycle of natural convention loop, and this precooling process is separated to two stages by the flange of first stage cold head of the cryocooler, which also play a role as a thermal boundary to reduce the conduction heat leak to the 4 K region by intercepting the heat at an intermediate temperature, and heat exchanges are equipped on the surface of the cryocooler to enhance heat transfer process. The liquefier has obtained a high efficient rate of over 18 L/day at 115 kPa.

The helium liquefier is also appropriate to be used in various cryogenic systems where liquid helium is needed. As a typical application, a helium recondensation cryostat for scientific experiments in pulsed
high magnetic fields has been developed. The performance of this helium recondensation cryostat will be fully described in another publication.

2. Design and experimental setup

For an ideal liquefaction, the heat load of helium can be calculated by the enthalpy.

\[ Q = \dot{m}\Delta h \]

\[ \Delta h = \int_{T_{bp}}^{T_H} C_p dT + h_{fg} \]

where \( Q \) is the heat load and \( \dot{m} \) is the mass flow rate. \( T_H \) is the high temperature of helium gas. \( T_{bp} \) is the boiling point of helium and \( h_{fg} \) is its latent heat. Since helium is a good approximation to an ideal monatomic gas, the heat capacity of helium \( C_p \) is nearly a constant.

Therefore, the key point to prove the efficiency of a helium liquefaction system is the precooling of helium gas [5]. When a liquid nitrogen (LN\(_2\)) cold trap is added, the temperature of incoming gas is being cooled to 77 K from 300 K, which means the cooling power of cryocooler can be used more efficiently. Heat exchangers equipped on the regenerators of GM cryocooler can also help precool the helium gas before it reaching the condenser.

Figure 1 shows a schematic of helium liquefier. The helium gas to be liquefied is supplied by a gas cylinder (a) with pressure reducing valve (b). The liquefaction rate is indicated from the helium mass flow which is precisely measured by a mass flow controller (c) (MKS, model GV50A). The pressure inside the dewar is monitored by a pressure gauge (e) (Fluke, model 700G-04) and maintained constant by changing the mass flow. A self-made liquid helium probe (f) is used to monitor the liquid level. The probe is a diode thermometer (Lake Shore, model DT 670) equipped at the bottom of an epoxy tube (ø 5 mm × 0.5 mm, length: 800 mm). The tube has many holes (ø 2 mm) to avoid the difference in pressure inside and outside of tube which will affect the temperature measurement of the probe. The liquid helium level probe is set at a default position and the temperature of the probe will have an obvious sharp decrease and then be stable when the liquid helium level reaches the position. Two other thermometers of the same model are fixed to the first stage cold head and the second stage cold head (with the condenser), and the temperature data is collected by a temperature controller (Lake Shore, model 335).
For the liquefier described in figure 1, helium gas is preliminarily cooled by passing through a LN$_2$ cold trap. The cold trap is a circular container equipped on the top of the vacuum vessel and has a heat exchanger wrapped around its inner wall. Another function of the cold trap is to supply cold capacity for the radiation shield which is made by cooper and has aluminum foil on the surface. The cold trap can hold 7.8 liters of LN$_2$ and need to be filled every 3 hours to make sure the heat exchanger is totally under the LN$_2$ when carrying out the liquefaction experiments.

Figure 2 shows the details of separated two-stage precooling method is adopted in the small-scale helium liquefier. Helium gas supplied to the inside dewar will be cooled by first stage regenerator, first stage cold head, second stage regenerator and second stage cold head of the GM cryocooler with a nature convention flow. Between the flange of first stage cold head and the inner wall of dewar, an indium plate with small flow channel is added and separate the neck space of the dewar to two parts to form temperature gradients. The precooling process is separated to two parts by the flange of first stage cold head to make sure the helium gas can be cooled to about 50 K before passing through the surfaces of the second stage regenerator of the cryocooler for deeper precooling.

**Figure 2.** Separated two stage precooling structure of the helium liquefier

The precooling process is carried out by direct contact heat transfer between the helium gas and the GM cryocooler. In order to make the nature convention heat exchange process more effective, 6 pieces of copper plates are installed on the surface of the regenerators of the cryocooler (see details in figure 3). Eventually, liquid helium film is formed on the vertical surface of the condenser and get into the storage tank.

**Figure 3.** Photo of the measurement setup with the recondensing cooling system. (a) Photograph of heat exchangers on GM cryocooler; (b) the copper plate heat exchanger, thickness: 5 mm, with many holes of Ø1.8 mm; (c) condenser made of copper, Ø48 mm with holes of Ø3 mm, length: 30 mm.
3. Experiments and results

The helium liquefier works under a pressure of 2 psi inside the dewar for 11 hours and the pressure is enhanced by 2 psi every 3 or 4 hours. The pressure is controlled to be stable by changing the mass flow rate of helium gas. Figure 4 shows the temperature and mass flow rate variations during the first 10 hours of the experiment. It takes 7.2 hours for the liquid helium (LHe) vessel reaching a stable temperature of 4.352 K and starting to produce liquid helium.

![Figure 4. Temperature and mass flow rate variations during the first 10 hours.](image)

The mass flow is quite small and increasing slowly in the beginning four hours as the cooling power has almost totally been consumed in cooling down the warm dewar. When the temperature of the second stage cold head get lower than the first stage cold head, helium gas obtains much more cooling power from the second stage cold head, the mass flow suddenly increases quickly. And then the mass flow starts to decrease when the temperature of LHe vessel get lower than the first stage cold head, which means the helium gas in the vessel can be continually cooled only by the second stage cold head. With the temperature of second stage cold head reaching the lowest point of 4.15 K and being stable, the gas flow tends to be flat. Finally, when condensation started and forming droplets, the mass flow rate becomes steady and the liquefier enters a process of stable operation.

Figure 5 shows the record of mass flow during total experimental run. When the liquefier runs stably at a set pressure, the mass flow rate of helium gas remains relatively constant. At a pressure of 2 psi, the typical average mass flow rate is 9027 sccm (data from hour 8.5 to 10.5), thus a liquefaction rate of 96.7 g/h, corresponding to 18.57 L/day. And the average mass flow rate at 4 psi is 9595 sccm (data from hour 12.5 to 14.5), that means a liquefaction rate of 102.8 g/h. Mass flow rate is falling slowly because the liquid helium level is growing up and the volume for gas becomes smaller.

![Figure 5. Temperature of the LHe probe and the mass flow rate of different pressure.](image)
Figure 6 is the liquefaction rates at different pressures. When the working pressure of the helium liquefier rises, the liquefaction rate can be enhanced. It can be found in other references that the liquefaction rate will achieve maximum when a liquefaction system operates near the critical point of helium (about 220 kPa) [4], [5]. However, the condensation power of different pressures almost consistent as showed in figure 6:

$$Q_c = \dot{m} h_{fg} \approx \text{constnt} = 0.53 \, W$$

(3)

where $Q_c$ is the condensation power, $\dot{m}$ is the liquefaction rate, and $h_{fg}$ is the latent heat of helium. This result indicates the positive correlation between the pressure and the liquefaction rate is mainly due to the latent heat of helium decreases with increase of pressure.

![Figure 6. Liquefaction rate and condensation power of different pressure.](image)

4. Conclusions

A small-scale Helium liquefaction system using a 1.5 W @ 4.2 K GM cryocooler has been designed and tested. A liquefaction rate of 18.57 L/day has been obtained at a low operating pressure of 2 psi (absolute pressure near 115 kPa). The liquefaction yield would be enhanced by increasing the operation pressure. This system uses liquid nitrogen for precooling helium gas and cooling the radiation shield.

The liquefaction rate would be enhanced by increasing the operation pressure, which is mainly due to the latent heat of helium decreases with increase of pressure, and the condensation power ($\dot{m} h_{fg}$) of the liquefier under different pressures are nearly constant at a value of 0.53 W.

With modular design, the liquefaction system can also be equipped directly in low temperature systems to supply liquid helium, which is a good option for middle and small cryogenic laboratories to get rid of liquid helium dependence.

References

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