

Analysis of Present Status of the Helium Liquefaction Device

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Abstract

Liquid helium is widely used in scientific devices to offer a cryogenic temperature for superconductor. In addition, liquid helium is also the main mode of long-distance transportation of helium. In this paper, the main principle of helium liquefaction is discussed. The helium liquefaction devices around the world for scientific research and industry are concluded, as well as the liquefaction device producers.

Keywords

Liquid Helium; Principle; Scientific Research; Transportation; Producer.

1. Introduction

Helium is a colorless, odorless, non-toxic, non-flammable inert gas at room temperature and atmospheric pressure, and its chemical properties are extremely stable. Helium has a normal boiling point of $-268.93\text{ }^{\circ}\text{C}$ and a critical temperature of $-267.96\text{ }^{\circ}\text{C}$ [1], making it the most difficult gas to liquefy. One cubic meter liquid helium is equivalent to about 700.05m^3 of gaseous helium at 0°C , 101.325kPa . As a refrigerant, liquid helium has important applications in the fields of space technology, superconductivity technology and cryogenic electronics. At the same time, liquid helium is also an important carrier of helium transportation.

In terms of the application of space technology, liquid helium is mainly used to provide heat sink temperature below 20K for space environment simulation equipment to ensure the simulation accuracy of thermal equilibrium test and the requirements of extremely low temperature assessment for thermal vacuum test. In the field of superconductivity technology, liquid helium is used to provide a low-temperature superconducting environment for large scientific devices such as nuclear fusion devices, particle colliders and spallation neutron sources, so as to improve the magnetic field strength of the magnets to ensure the performance of the devices. In the field of cryogenic electronics, liquid helium is mainly used to provide extremely low temperatures for superconducting quantum chips and semiconductor quantum chips. In the field of helium storage and transportation, due to the shorter transportation cycle, higher efficiency and lower cost of liquid helium, liquid helium transportation is preferred for large-scale and long-distance helium transportation, and mobile liquid helium tank containers are mainly used for liquid helium transportation.

2. Technical Process of Helium Liquefaction

2.1. The First Liquefaction of Helium

Helium was first liquefied by Onnes in 1908. The highest conversion temperature of helium is about 39K , which means that the throttling of helium can only generate heat when the helium temperature is above 39K . Therefore, Onnes adopted liquid nitrogen and liquid hydrogen to precool helium before throttling.

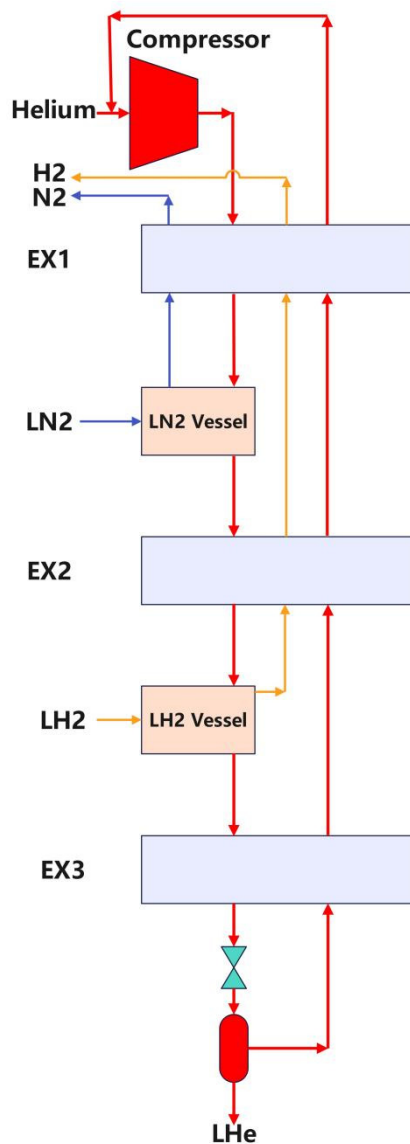


Figure 1. Schematic of Onner's Helium Liquefaction Process

In the refrigeration cycle with compression and throttling, there are a compressor and three heat exchangers. The compressed helium is first cooled in the first heat exchanger and then by the liquid nitrogen. After being cooled by the second heat exchanger, the liquid and the third heat exchanger, the helium is throttled to about 1 bar. The liquid helium after throttling is storage in a dewar while the gaseous helium returns to the heat exchanger to rewarm to normal temperature.

Onner's process of helium liquefaction is simple but with huge energy consumption. In addition, there is a risk of explosion because of the hydrogen. Therefore, Onner's process is barely used in industry.

2.2. Helium Liquefaction in Modern Industry

Compared to isentropic expansion, isentropic expansion can generate a larger temperature drop and has higher efficiency. Therefore, the Claude cycle adopts a cycle composed of liquid nitrogen, expander pre cooling, and a J-T throttling, as shown in **Figure**. Claude cycle was developed by George Claude, who established air liquid in 1902.[3]

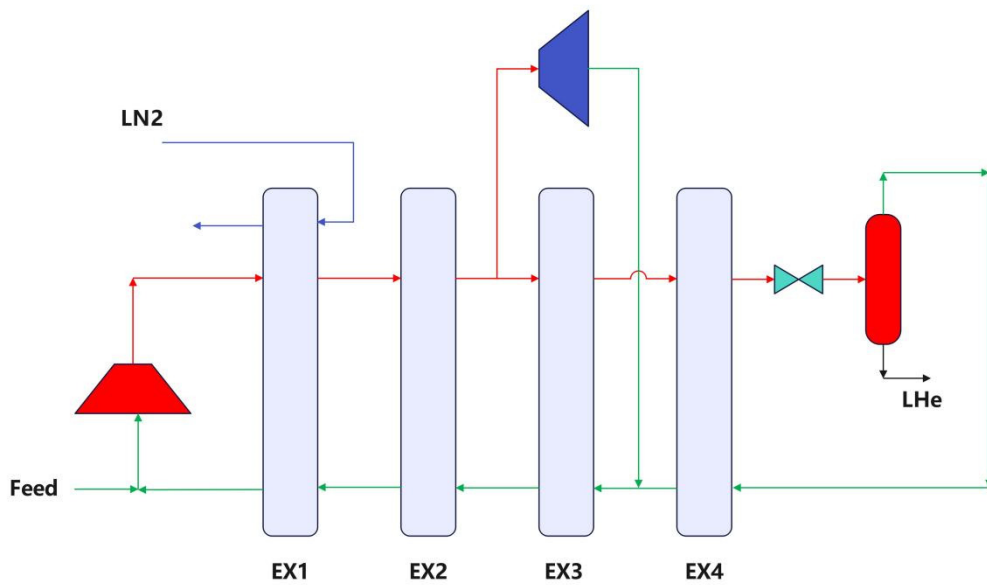


Figure 2. Schematic of Claude Cycle

Modern helium liquefaction systems often adopt an improved version of the Claude cycle, using a combination of liquid nitrogen pre-cooling, multiple expansion cooling, and J-T throttling refrigeration. The use of multiple expansion cooling can reduce the system's heat transfer temperature difference, thereby reducing irreversible losses and achieving higher system efficiency. However, it also increases system complexity, investment, and operating costs. At present, the common improved Claude cycle mainly includes Collins cycle and modified Claude cycle.

Collins Cycle including a liquid nitrogen pre-cooling, two parallel turbine expanders and a throttling valve[5]. Compared with the Claude Cycle, Collins Cycle added another turbine expander, which make it possible to liquefy helium without liquid nitrogen pre-cooling. However, researchers indicated that liquid nitrogen precooling in Collins Cycle could double the helium liquefaction rate[6].

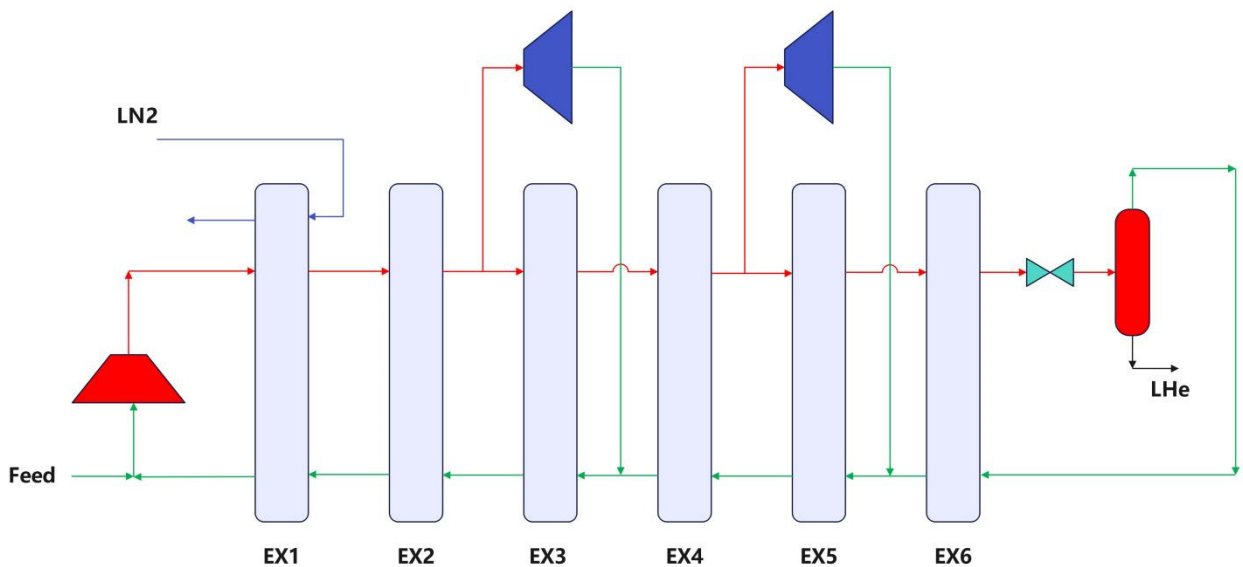


Figure 3. Schematic of Collins Cycle

The modified Claude Cycle is similar to the Collins Cycle, but with two turbine expanders in serial, as shown in **Figure**. The series connection of the two expansion stages reduces the expansion ratio of each stage, thus increasing the efficiency of the expander[7].

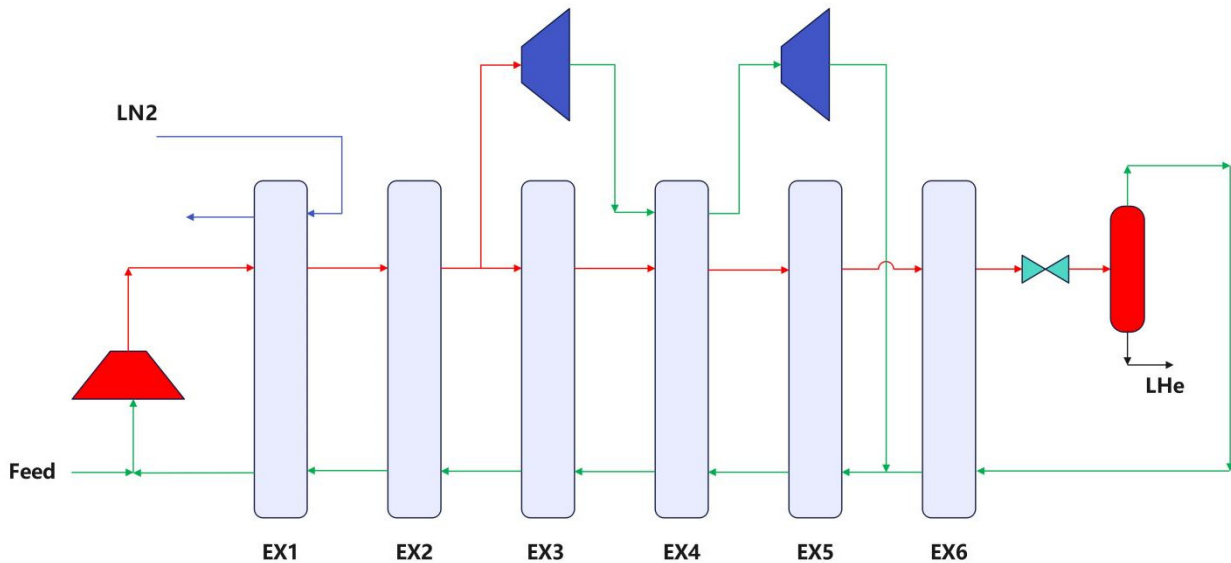


Figure 4. Schematic of Modified Claude Cycle

3. Helium Liquefaction Device around the World

The helium liquefaction device is mainly used to generate cryogenic temperatures under 4.5K for scientific research and for helium transportation in industry.

3.1. Helium Liquefaction Device for Scientific Research

Table 1. Parameters of Helium Liquefaction Device in Large-scale Scientific Devices

Device	Country/Zone	Capacity
RHIC[8]-[10]	USA	9.4kW@4.5K
LEP[11]	Europe	15kW@4.5K × 4
LHC[12]	Europe	18kW@4.5K
ESS[13]	Europe	3.05kW@4.5K
ITER[14]	France	70kW@4.5K
LHD[15]	Japan	5.77kW@4.5K
HERA[16]	Germany	40g/s LHe
TESLA[17]	Germany	86W@2K
SST-1[18]	India	1kW@4.5K
SRRC[19]	Taiwan	110L/h LHe
SHMFF[20]	China	110L/h LHe
EASR[21]	China	2kW@4.5K
CSNS[22]	China	2kW@4.5K
BEPC[23]	China	500W@4.5K
HL-2A[24]	China	500W@4.5K
SSRF[25]	China	681W@4.5K

Large-scale scientific device like Steady-state strong magnetic field devices, experimental fusion devices, synchrotron light sources, X-ray free-electron laser devices, particle colliders, scattered neutron sources, etc. are important experimental platforms for solving technical

problems in basic research and frontier science. The performance of those large -scale scientific device is greatly influenced by the strength of the magnetic field in the device. For conventional magnets, the simple way to strengthen the magnetic field is to increase the current, inducing high heat generation and consequently decreasing the performance of the magnet, while the superconductors are the perfect solution to the problem. The currently used superconductors is NbTi and Nb₃Sn, whose critical temperature is about 9.2K and 17.5K, which can only produce by liquid helium. Therefore for, the helium liquefaction device is widely used in the large-scale scientific device. **Table 1** gives the parameters of the helium liquefaction device for scientific research around the world.

3.2. Helium Liquefaction Device in Industry

Normally, helium is transported in high pressure(20MPa) tube bundles and liquid helium tankers. The density of liquid helium is about 4.3 times of that of 20MPa gaseous helium at room temperature, therefore, liquid helium tankers are adopted for long-distance transportation. Large helium liquefaction devices are constructed in helium plants in countries with rich helium like Qatar, America, Algeria, Russia, etc. **Table 2** indicates the helium production in main helium-producing countries in 2024.

Table 2. Helium Production in 2024

Origin	Yield, × 10 ⁷ Nm ³
Qatar	6.6
USA (extracted from NG)	6
USA (from Cliffside Field)	
Algeria	1
Russia	0.8
Canada	0.4
Poland	0.3
Australia	0.1
South Africa	<0.05

The helium liquefaction plant in Qatar is located in Ras Laffan Industrial City, Qatar. There are three phases of helium liquefaction plant, all of which have been put into operation, with the output of liquid helium in Phase I being about 3.1m³/h, in Phase II being about 6.7m³/h, and in Phase III being about 2m³/h. The helium liquefaction equipment is supplied by AIR LIQUIDE. The United States has a liquid helium plant in Texas with helium liquefaction equipment supplied by Linde.

Algeria has a liquid helium plant in Arzew, with helium liquefaction equipment supplied by Linde.

There are currently three liquid helium plants in Russia, located in Irkutsk, Orenburg and Amur, with a production capacity of about 1.2m³/h, 1.1m³/h, 1.1m³/h. the liquid helium plant in Irkutsk uses a liquid nitrogen pre-cooling, a two-stage turbine expander in series and a piston expander at 4.5K.

Canadian helium plants are operated by North American Helium Corporation, which currently has seven helium production plants in operation, as well as a liquid helium plant with an unknown amount of liquid helium production.

In China, liquid helium plants that have been put into operation at present include a 140L/h liquid helium plant in Erdos, Inner Mongolia, and a 107L/h liquid helium plant in Inner Mongolia.

4. Suppliers of Liquefaction Equipment

Currently, the international market for large helium liquefaction equipment is dominated by Air Liquide and Linde. Air Liquide's standard helium liquefaction equipment, the HELIAL series, consists of three series: SL, ML and LL, and the standard helium liquefaction equipment has a production capacity of about 30 to 330 L/h. Air Liquide can also customize the helium liquefaction equipment according to the customer's requirements, and the maximum production capacity of the customized equipment is 3,100 L/h. Qatar's helium project has used several sets of large-scale helium liquefaction equipment from Air Liquide, with a single unit achieving a capacity of 3,100 L/h.

Linde's standard helium liquefiers are available in a wide range of sizes, including the L70, L140 and L280 series, with helium outputs ranging from 40 to 70, 90 to 140, and 200 to 290 L/h, respectively. The Linde Group can also customize helium liquefiers with a capacity of 250-3500 L/h to meet customers' requirements.

5. Conclusion

In this paper, the basic principle of helium liquefaction is discussed. The helium liquefaction devices around the world for both scientific research and industrial purpose are also indicated.

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