Hydrogen Production
– Development of Hydrogen Liquefaction Systems

Hydrogen liquefaction systems, which require advanced cryogenic technology, are an important factor in the global supply chain of liquefied hydrogen. Kawasaki has built the Japan's first domestically developed commercial-scale liquefaction system that can liquefy approximately five tons of hydrogen per day. Since the first successful liquefaction in 2014, Kawasaki has improved liquefaction efficiency by approximately 20% with its new liquefier, and has also demonstrated the reliability of the liquefier through long-term operation. Kawasaki has begun technical studies aimed at further increasing the size and efficiency of liquefiers.

Introduction

One method of efficiently storing and transporting a large amount of hydrogen is liquefying it. Hydrogen shrinks to 1/800 of its original volume when liquefied at -253°C, which makes it extremely easy to store and transport. And when converted back into gaseous hydrogen, liquefied hydrogen only requires heat exchange with the atmosphere and so does not consume any extra energy. In addition, as liquefied hydrogen has extremely high purity, it has many benefits, including that once gasified you can instantly use the gaseous hydrogen in a fuel cell.

1 Background

Cost reduction in hydrogen procurement and supply is indispensable to the spread of hydrogen energy. As liquefied hydrogen is presumed to account for approximately 30% of the entire hydrogen cost in a global supply chain when using liquefied hydrogen as a carrier, cost reduction in hydrogen liquefaction systems and by efficiency improvement would have a great effect.

A commercial-scale hydrogen liquefaction system requires expertise and know-how on liquefied hydrogen handling and cryogenic technologies. As such, there are only three companies in the world that possess design and manufacturing technologies for such systems, and all of them are major industrial gas companies in Europe or the U.S. In Japan there are three commercial-scale hydrogen liquefaction plants, but all their liquefiers, which are the main part of the system, were made abroad. Even outside of Japan, more plants are being built as more fuel cell vehicles are being used, but the owners of the plants are the same industrial gas companies in Europe or the U.S. And liquefier market formation with new energy companies has not fully started yet.

Kawasaki has been working on consistent technology development and commercialization covering the entire hydrogen energy supply chain to realize a hydrogen-based society. Given the importance of a hydrogen liquefaction system to realizing a hydrogen-based society, we decided to proceed with development using our own technologies and make such systems in Japan for the first time.

2 Development scheme

Hydrogen liquefaction requires extremely advanced cryogenic technology. About 30 years ago, Kawasaki developed a helium liquefier for a cryogenic research institute[1]. With the design materials from that time and some advice from persons with experience, we have carried out research and development on hydrogen liquefaction technology since around 2010.

In 2011, we started a demonstration project to construct a prototype liquefier and its demonstration plant at our Harima Works in order to operate Japan's first hydrogen liquefier[2].

At the same time, by using the expertise and know-how obtained from such development, we started another development project on a new liquefier, which will be the basis for a commercialized one, from the last phase of the prototype liquefier demonstration.

3 Hydrogen Liquefaction System and Kawasaki's Development Challenges

(1) Hydrogen liquefaction system

A schematic diagram of our demonstration facility for a hydrogen liquefaction system is shown in **Fig. 1**. The facility consists of a hydrogen liquefier as well as equipment such as liquefied hydrogen storage tanks, liquid nitrogen storage tanks, which is used for precooling, and hydrogen compressors.

The schematic process flow of the hydrogen liquefaction system is shown in **Fig. 2**. hydrogen feed gas

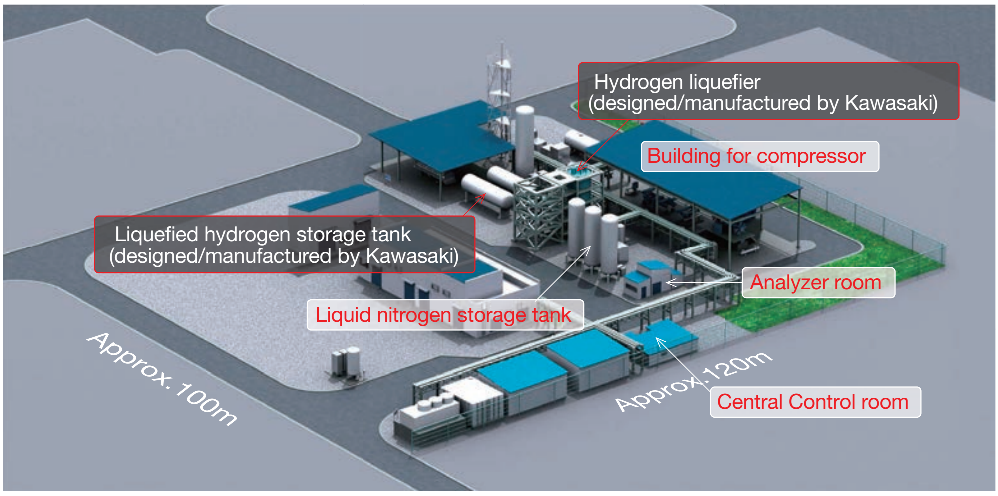

Fig. 1 Schematic diagram of hydrogen liquefaction system (demonstration facility in Harima Works)

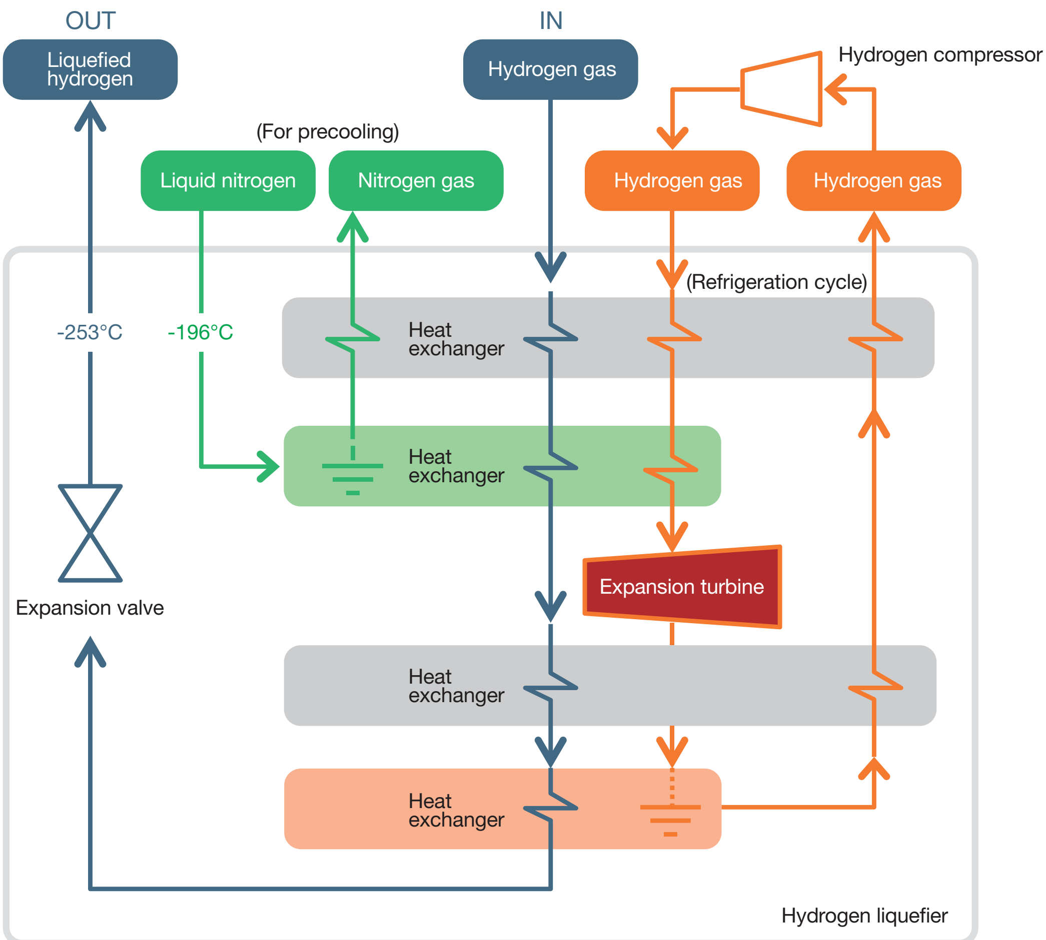

Fig. 2 Schematic process flow diagram of hydrogen liquefaction system

compressed by the hydrogen compressor is cooled to almost -200°C by liquid nitrogen for precooling, it is cooled again by a few dozen degrees using the cold energy from a refrigeration cycle, and then it is liquefied through adiabatic expansion through an expansion valve. This refrigeration cycle adopts a hydrogen Claude cycle (a refrigeration cycle combining expansion turbines and an expansion valve), which means the system uses hydrogen to cool hydrogen.

(2) Development challenges

There was a wide range of development challenges as we had never developed a hydrogen liquefier before and needed to design it on a large scale. Major challenges were:

① Process design
② Structure, insulation, and sealing of hydrogen liquefiers
③ Expansion turbine
④ Operation control for start-and-stop, load change, and other operations
⑤ Gas purity management
⑥ Facility/operation safety

For a new liquefier, there are other challenges, such as further improvement of its efficiency and reliability demonstration for future commercialization.

And as we are an equipment manufacturer and did not have sufficient expertise on liquefaction plant operation including facility operation/maintenance or organizations for such operations, establishing each of these toward demonstration operation was another big challenge for us.

4 Prototype liquefier

(1) Design and manufacturing

Our prototype liquefier and its surroundings are shown in the picture at the beginning of this chapter. Because we have experience manufacturing large-scale structures and cryogenic-related equipment including LNG storage tanks, we successfully manufactured the hydrogen liquefier and the liquefied hydrogen storage tank we developed this time without installing any new infrastructure.

Although this system was built for the purpose of technology development, in order to obtain and demonstrate commercial-scale liquefaction technologies, we built it on a commercial scale, which can produce approximately five tons of liquefied hydrogen per day.

(i) Process design

We designed the process ourselves and optimized the compressor arrangement, the number of stages of the expansion turbines and their load distribution, and the pressure in each line. We also conducted element tests such as the pressure drop characteristics of an adsorber to adsorb impurities, and then reflected those results in the design.

(ii) Structure, insulation, and sealing

When designing the hydrogen liquefier's structure, we took into consideration standards and regulations of seismic design, referring to a helium liquefier we had developed. To prevent heat input from the outside of the hydrogen liquefier, we also insulated the support of the internal equipment.

In order to make the hydrogen liquefier vacuum-insulated, we needed to maintain a high vacuum on the inside. Consequently, welded parts and sealed flanges required extremely tight seals. Making the most of our high precision manufacturing and extremely tight sealing, we were able to pass a helium leak test. For the insulating materials applied to the surfaces of the internal equipment, we applied our cumulated know-how on design and construction.

(iii) Expansion turbine

The expansion turbine, shown in **Fig. 3**, is a key piece of hardware used to generate the cold heat required for liquefaction. In designing the optimal process, the turbine needed to be much smaller than the hydrogen liquefier (approximately four meters in diameter, and twelve meters high), and rotate at a speed of more than 100,000 revolutions per minute. So, we developed a new gas bearing using hydrogen gas to support the rotating shaft, instead of using the typical oil or ball bearing. This gas bearing also offers benefits such as significant reduction of friction loss due to the bearing and prevention of system oil contamination. Lastly, in designing aerodynamics and rotor dynamics, we applied our high-speed rotating machinery technology for gas turbines and jet engines.

(iv) Operation control

As the behavior of a hydrogen liquefaction system is very complicated, we used simulations to design the control logic. There were some parts that had to be adjusted step by step during the actual operation, and we continued making slight improvements based on the data obtained from the demonstration operation.

(v) Purity management

In a -253°C environment where hydrogen gets liquefied, every substance except helium and hydrogen freezes and turns into a solid, which means that any impurities in the hydrogen gas may clog the system. That is why hydrogen gas purity management is so important, and why we monitored an analyzer to make sure that the level of impurities was always less than a ppm. This allowed us to produce liquefied hydrogen with purity higher than 99.999%, meaning that once gasified, you can use it directly for a fuel cell, as mentioned above.

(vi) Safety

To ensure safe facility design, we conducted HAZOP and FMEA ourselves, which are system engineering methods of analyzing the reliability and safety of plant

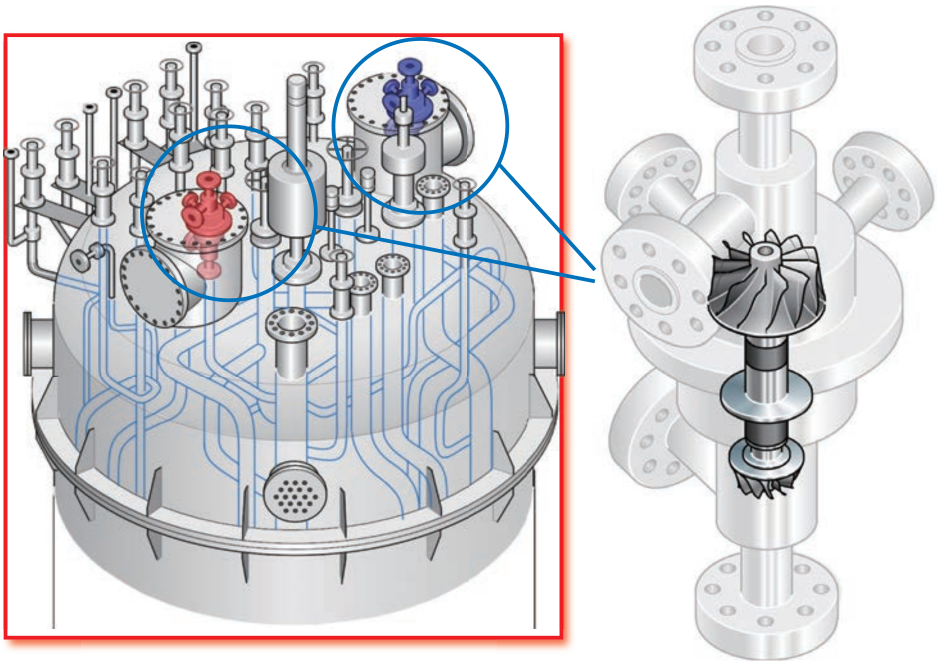

Fig. 3 Hydrogen liquefier (upper part) and expansion turbine

facilities, and we had several independent organizations review the level of safety. For our facility demonstration operation, we put an organization and system in place for operation and maintenance, communicated closely with relevant administrative authorities, and proceeded with operations while preventing any safety issues from occurring.

(2) Demonstration operation

In September 2014 we successfully liquefied hydrogen for the first time. After that, we verified our process design for this prototype liquefier, and tested the performance of the expansion turbines, the controllability, and the adsorber, among other things. We also measured the vibration and stress of the internal piping and confirmed its soundness.

After that, we continued to update the facility and the control software to improve the performance and reliability of the expansion turbines and plant controllability, which enabled us to automatically start/stop the expansion turbines and automatically control the liquefaction operation (constant loading and load change). The system cleared multiple interlock tests without causing any trouble to the facility, fully confirming the safety of the system as well. This prototype liquefier demonstration operation was completed at the end of fiscal 2016.

5 New liquefier

(1) Design and manufacturing

For our new liquefier, we improved the process in order to improve liquefaction efficiency, and increased the design accuracy by using the data of the prototype liquefier. To improve its efficiency even further, we added an ejector that collects boil-off gas in the liquefied hydrogen storage tank along with the cold heat. We adopted almost the same expansion turbine as the prototype's, valuing the performance it demonstrated. To make the liquefier smaller, we reconsidered the layout of the internal equipment, and made it 0.5 meters smaller than the prototype in diameter and height, as shown in **Fig. 4**. This reduced the weight by 30% from the prototype and contributed to cost reduction.

After completing the prototype demonstration operation, we worked on the design and manufacture of a new liquefier, and replaced the prototype with the new one in March 2019 as shown in **Fig. 5**. After that, we adjusted the peripheral equipment in accordance with the new liquefier and started trial operation in August 2019.

(2) Demonstration operation of the new liquefier

We started full demonstration operation of the new liquefier in October 2019. Thanks to our achievement and experience gained with the prototype liquefier, we successfully achieved liquefaction without facing any problems, even in the first operation. In the performance test performed later, we confirmed that the liquefaction efficiency was improved by approximately 20% from the prototype. We also confirmed that the added ejector demonstrated the designed performance.

As this new liquefier is the base for the commercialized one, stable performance, reliable controllability and facility

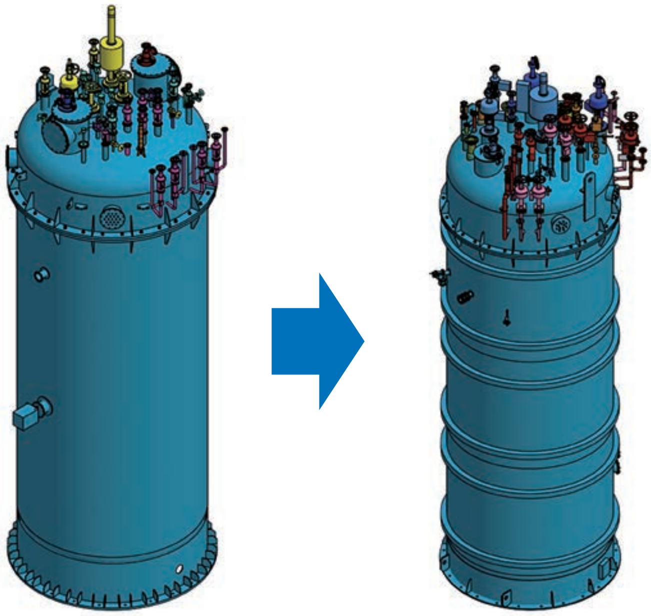

Fig. 4 Prototype liquefier (left) and new liquefier (right)

Fig. 5 Installation of new liquefier

durability must be demonstrated even in long-term operation. To that end, we operated the equipment for 3,000 hours non-stop from December 2019 to April 2020. During this time, in addition to constant load operation, we confirmed the controllability during load changes and conducted a performance test of the adsorber on adsorption of impurities contained in the feed gas. No trouble occurred in any of these operations.

Conclusion

Based on the technologies that the new liquefier demonstrated, Kawasaki is planning to offer a product lineup of hydrogen liquefaction systems, the liquefaction capacity of which will range from 5 to 25 tons per day. Considering the coming hydrogen-based society, the cost of liquefied hydrogen needs to be reduced further. Because of this, we anticipate that designing a new process that substantially increases liquefaction efficiency will be required, as will making the system far larger. We have already started technical studies to meet such requirements.

Furthermore, we believe that what enabled us to have continued accident- and injury-free demonstration operation for the six years starting from the prototype phase of hydrogen liquefiers was the high awareness of safety of all the individuals involved and the fully safety-conscious system design.

We carried out the abovementioned development of the hydrogen liquefaction system as one of our projects, but the preparation and arrangement of the peripheral equipment of the hydrogen liquefier was partially subsidized by the Ministry of Economy, Trade and Industry. We would like to express our sincere gratitude for supporting us.

Reference

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2) Kamiya, Isano, Kariya et al: "Technologies of hydrogen liquefaction, transport and storage — Paving the way to a hydrogen fueled future," Kawasaki Technical Review No. 176, pp. 51–58 (2016)

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