Hydrogen Storage
– Development of Liquefied Hydrogen Terminal

Photographed in May 2020

Regarding a liquefied hydrogen terminal, which as an element of a hydrogen energy supply chain stores liquefied hydrogen, we constructed a pilot-scale loading/unloading terminal for demonstration testing in fiscal 2020. And looking to future commercialization, we have been working on increasing the scale of development and international standardization.

Introduction

In order to establish a hydrogen energy supply chain, a liquefied hydrogen terminal for unloading and storing liquefied hydrogen shipped from overseas and for supplying the liquefied hydrogen to power generation facilities and hydrogen stations is needed.

1 Background

Most of the large-scale liquefied hydrogen terminals that have been constructed around the world are related to rocket launch facilities. You can find spherical storage tanks like the 3,218 m^3 tank at NASA's Kennedy Space Center, and the 540 m^3 tank at the Tanegashima Space Center that Kawasaki delivered, but neither of these is loading/unloading terminals for ships. In recent years, studies on large-scale storage tanks are under way. For example, the Kennedy Space Center has been constructing a liquefied hydrogen storage tank with a capacity of approximately 4,700 m^3 since 2018. Toyo Kanetsu K.K. is also working on the development of a 10,000 m^3 liquefied hydrogen storage tank.

There is also a need for a loading arm system (LAS), which connects to a ship and sends liquefied hydrogen to a terminal. There is a product for liquefied natural gas (LNG), but it is for working with temperatures around -160°C and no product exists that can handle-253°C, which is the temperature of liquefied hydrogen.

As it stands there are no liquefied hydrogen terminals nor methods for unloading it from a ship, so many different pieces of equipment must be developed. International standards for a liquefied hydrogen terminal have yet to be determined, so to build a hydrogen-based society, international rules must be established in addition to the required equipment. Not only will such rules make it easier for developed equipment to enter the world market, but they will ease the burden of constructing and operating facilities for safely storing and transporting produced hydrogen in developing countries having difficulty formulating their own standards. This is especially important in the case of LAS because if different terminals use different systems, ships may have difficulty loading and unloading the liquefied hydrogen. Hence, the importance of standard development.

2 Development scheme

Since fiscal 2015 Kawasaki has been working to establish a hydrogen energy supply chain using a liquefied hydrogen carrier of approximately 1/100 the capacity of a commercial scale one as a grant project for the New Energy and Industrial Technology Development Organization (NEDO), called the Demonstration Project for the Establishment of a Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal (hereinafter, "the pilot demonstration")[1].

In the pilot demonstration, we will verify technologies on handling (loading/unloading) liquefied hydrogen between a carrier's cargo tank and an on-shore tank, which have many elements to address, especially from a technological standpoint. And by scaling up the liquefied hydrogen tank at the Tanegashima Space Center, we will manufacture and install a 2,500 m^3 nominal geometrical capacity tank, which will be the largest in Japan, and store liquefied hydrogen transported by a liquefied hydrogen carrier in the tank.

Figure 1 is a rendering of a liquefied hydrogen loading/unloading demonstration terminal in Kobe for verifying loading/unloading technologies. The terminal is located on the northeast shore of Kobe Airport Island. The site preparation and the installation of mooring facilities were conducted by Kobe City in fiscal 2017. The construction of the terminal started in April 2018 and then its trial operation was finished by the end of May 2020. We will complete our demonstration of liquefied hydrogen marine transportation between Australia and Japan before the end of fiscal 2020.

3 Liquefied hydrogen terminal

The liquefied hydrogen terminal consists of a liquefied hydrogen storage tank for storing liquefied hydrogen, a LAS to load/unload liquefied hydrogen between a carrier and the shore, and ancillary facilities. The ancillary facilities for handling hydrogen gas that we installed include a boil-off gas (BOG) compressor to compress hydrogen gas that evaporates from the liquefied hydrogen storage tank, a BOG holder to store the compressed hydrogen gas **(Fig. 2)**, and a vent stack to adequately release hydrogen gas that is generated while liquefied hydrogen is being loaded/unloaded. The hydrogen gas stored in the BOG holder is used for gas replacement in the terminal facilities and as

Fig. 1 Rendering image of liquefied hydrogen loading/unloading demonstration terminal in Kobe

Fig. 2 BOG holder

backup for unloading liquefied hydrogen from a carrier. The terminal has equipment for transferring liquefied hydrogen from a liquefied hydrogen tank lorry to the liquefied hydrogen storage tank.

(1) Liquefied hydrogen storage tank

The liquefied hydrogen storage tank, shown in **Fig. 3**, is a spherical double-wall vacuum tank with a 2,500 m^3 nominal geometrical capacity. The tank receives and stores liquefied hydrogen transported from Australia, and also stores liquefied hydrogen transported by land from sites in Japan so it can be loaded into liquefied hydrogen carriers initially.

In order to store liquefied hydrogen for a long time while keeping lowevaporation loss, a liquefied hydrogen storage tank requires better thermal insulation than an LNG storage tank. Because of this, we adopted a vacuum insulation system. The largest liquefied hydrogen storage tank in Japan was the 540 m^3 tank at the Tanegashima Space Center, but our storage tank will have at least four times the capacity. As shown in **Fig. 4**, we adopted a perlite vacuum insulation system, enhancing the thermal insulation by filling the space between the inner and outer spherical tanks with perlite, a thermal insulation material, and then creating a vacuum.

To increase the size, we have been studying the most appropriate manufacturing method for welding thick plate materials at the construction site rather than at a factory and the optimum plate cutting plan to enhance construction efficiency. Through this process, we have

Fig. 3 Liquefied hydrogen storage tank

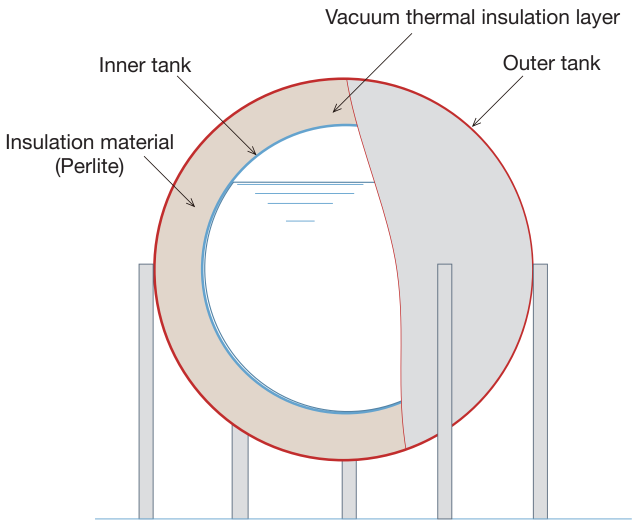

Fig. 4 Conceptual diagram of vacuum thermal insulation structure

been accumulating expertise with the aim of manufacturing such large tanks in the future. We have also been studying the operation of large tanks like these, operations such as hydrogen gas replacement before liquefied hydrogen is recharged and optimization of tank cooling, on which a demonstration will be conducted in fiscal 2020.

(2) Loading arm system

A loading arm system (LAS) is a facility that is installed on shore that connects to a liquefied hydrogen carrier moored at sea to load and unload liquefied hydrogen. Once the carrier reaches the shore, the LAS is connected to the carrier’s manifold and it transports liquefied hydrogen while following the swaying movement of the carrier due to the waves.

A LAS that uses vacuum thermal insulation should be used for liquefied hydrogen as it requires better thermal insulation than existing LAS systems for LNG. At the same time, flexibility or mobility is also required for the system to follow the swaying movement caused by the waves. To that end, we adopted a double-wall vacuum flexible hose for our LAS.

In order to move with the swaying movement of the liquefied hydrogen carrier, the LAS structure was designed to hang the flexible hose with a crane-like arm. **Figure 5** is an image of a ship connected to the LAS. **Figure 6** is the LAS for the demonstration project under construction at a factory. As we did not have experience making anything like this arm structure for hanging a flexible hose even for LNG applications,we conducted structure analysis studies in many different arm positions. To confirm its durability against repeated displacement in cryogenic conditions, we manufactured a prototype and conducted different performance tests using liquefied hydrogen.

Not only is this LAS equipped with a system to follow swaying movements caused by waves but it also has an emergency release system (ERS) for the carrier to leave

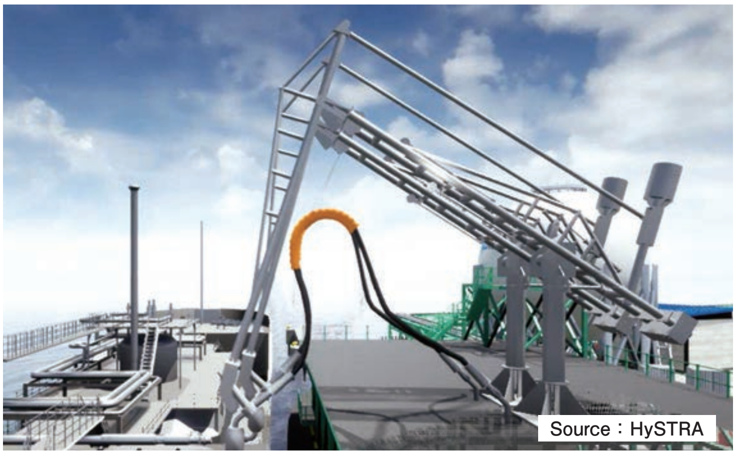

Fig. 5 Image of a ship connecting to terminal

Fig. 6 Loading arm systems for demonstration project

the shore safely and promptly in an emergency. If a carrier displaces beyond tolerance, the ERS will automatically activate to minimize liquefied hydrogen leak to the outside as it detaches. In the event of an emergency such as a fire, the ERS can be started manually with the release switch. While the LAS for LNG does have an ERS, the LAS structure for liquefied hydrogen has a different structure as it adopts vacuum thermal insulation to increase the thermal insulation properties, the same as the flexible hose, and in that it suppresses heat transfer from the valve that will be closed in an emergency. We used our thermal stress analysis technology under cryogenic conditions for this structure development. We developed these pieces of equipment under the Cross-ministerial Strategic Innovation Promotion Program (SIP) by the Japanese Cabinet Office, manufactured a prototype, and conducted tests such as a release test in which a tank was filled with liquefied hydrogen and a closing performance test after the ERS disconnected[2].

The term "LAS" covers all of the pieces of equipment that are part of the LAS system, including the double-wall vacuum flexible hose, the crane-shaped arm, the ERS, and the hydraulic system controller.

4 Future endeavors

(1) Making larger liquefied hydrogen storage tanks

The spherical vacuum thermal insulated liquefied hydrogen storage tank constructed in the pilot project requires making its outer tank thicker to prevent buckling caused by the internal vacuum pressure. In the case of a storage tank that is tens of thousands of cubic meters in size, as would be needed at the commercial stage, the outer tank needs to be made very thick, which poses difficulties in obtaining and manufacturing plate materials.

We are therefore developing a large-scale liquefied hydrogen storage tank with a new structure toward future commercialization under a grant project by NEDO called the Development of Large-scale Equipment for the Transport and Storage of Liquefied Hydrogen and Equipment for Liquefied Hydrogen Unloading Terminals. One of the structures being studied is a flat-bottomed cylinder, as shown in **Fig. 7**, which has higher volume efficiency than the spherical shape used for large LNG

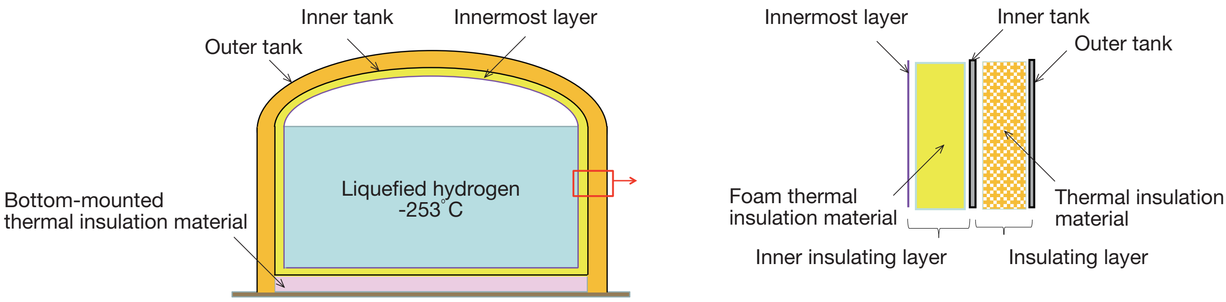

Fig. 7 Structural design of a large-scale tank

Fig. 8 Liquefied hydrogen loading arm systems for commercial use

tanks. Using a non-vacuum structure with hydrogen gas at atmospheric pressure between the inner and outer tanks allows us to prevent buckling caused by vacuum pressure, which would be a problem if a vacuum thermal insulation structure were used. We are also considering applying gas barrier materials to the surfaces of thermal insulation materials in order to prevent the deterioration of the thermal insulation properties due to hydrogen gas permeating into the foam thermal insulation materials. The concept of this structure is to reform the existing LNG storage tank, which will be effective as we gradually replace LNG with hydrogen at the introduction phase of a hydrogen-based society.

(2) Making the LAS for liquefied hydrogen larger

Given that a commercial LAS must be bigger in diameter, considering installation area and its weight, the main method of following the swaying movement of a carrier will be to adopt the swivel joint used in LNG terminals. We thus manufactured an experimental LAS of this type, as shown in **Fig. 8**, in a joint development under the SIP program with Tokyo Boeki Engineering, Ltd., which holds a dominant share of the LAS systems used for LNG in the world, and confirmed that it works normally. We will continue demonstration tests using liquefied hydrogen and complete this development.

(3) International standardization

Currently, the only international standards on LAS for low temperature use are those that the International Organization for Standardization (ISO) set for LNG, but they have yet to be established for liquid hydrogen. So, we have been working on establishing international standards for LAS for use with liquefied hydrogen. We set up a working group in the ISO and have been holding discussions with experts from various countries when we have opportunity such as at regular conferences held in Japan or other countries. In oil- and gas-related standardization in the past, energy companies in Europe or the U.S. took the initiative in many cases but in this working group, chaired by the Japan Ship Technology Research Association, Kawasaki serves as Project Leader and leads the discussions. We are planning to continue discussions with various countries and achieve ISO standardization in 2022.

In the future, we will work on the international standardization of liquefied hydrogen equipment other than LAS to contribute to the establishment of a safe liquefied hydrogen energy supply chain.


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Conclusion

To commercialize a liquefied hydrogen terminal in 2030, Kawasaki is steadily preparing for loading/unloading demonstrations by constructing small-scale demonstration facilities, and we are developing commercial-scale equipment at the same time. Through completing such demonstrations and development and verifying that facilities conform to commercial requirements, we will continuously move forward toward the realization of a commercial-scale liquefied hydrogen energy supply chain.

Reference

1) H. Suzuki, T. Yoshiyama, K. Shindo, and M. Nishimura, "International Liquefied Hydrogen Supply Chain," International Conference on Power Engineering-2019)
2) A. Inomata, T. Umemura, J. Kawaguchi, T. Kawai, Y. Naruo, Y. Maru, T. Senda and M. Takeda, "Performance test and analysis of the developed emergency release system for liquefied hydrogen installed in loading systems," Materials Science and Engineering, 502 (2019)