Hydrogen Transportation – Development of Liquefied Hydrogen Carrier

Kawasaki has developed and built a liquefied hydrogen carrier to transport a large volume of hydrogen in the CO_2-free hydrogen energy supply chain. The carrier's large-sized tank for liquefied hydrogen employs a vacuum insulation system and will have come to realize the world's best level of thermal insulation performance. Through the demonstration of marine transportation between Japan and Australia starting in fiscal 2020, we aim to achieve large-volume transportation while ensuring safety.

Introduction

The indispensable foundation for realizing a hydrogen energy supply chain is to transport a large volume of hydrogen produced using the abundant resources of countries overseas to Japan safely and efficiently.

1 Background

The states hydrogen can be in for transportation include high pressure gas and liquid. High pressure gas is used to transport a relatively small volume of hydrogen to sites such as a hydrogen station for fuel cell vehicles. There is a limitation on how high the pressure can be increased in consideration of safely storing compressed hydrogen gas in a storage tank, but it has advantages in that you can use the gas with relatively simple equipment and operation at the demand sites. On the other hand, for mass transportation, liquid is more advantageous. When hydrogen is liquefied, its volume at atmospheric pressure becomes 1/800 that of its gas state. However, its temperature is -253°C, much lower than that of liquefied natural gas (LNG), which means that it requires special equipment and countermeasures for storage and handling. For this reason, there has been almost no marine transportation of liquefied hydrogen. Methods of converting hydrogen into an organic compound, such as ammonia and methylcyclohexane, for easy hydrogen transportation are also being studied. A compound would not require cryogenic handling, but it has its challenges in that it would require handling of toxic substances and extra energy to extract the hydrogen.

Kawasaki has developed a trailer for transporting high-pressure gaseous hydrogen by land and a container for transporting liquefied hydrogen by land and has already put them to practical use. The trailer employs a 45 MPa pressure-resistant compound tank, and is capable of transporting 360 kg of high-pressure hydrogen gas, which can refill 72 fuel cell vehicles. The container carries 2.8 tons of liquefied hydrogen in a vessel with vacuum and a multi-layer insulated tank complying with the ISO standard for a 40-foot container.

Based on our design and manufacturing technologies for LNG carriers and on-shore liquefied hydrogen storage tanks, we are now aiming to be the first in the world to establish design and manufacturing technologies for a liquefied hydrogen carrier that will support the transportation part of a CO_2-free hydrogen energy supply chain. In the Front-end Engineering Design (FEED) phase that lasted until fiscal 2016, we carried out element tests and studies on specifications, and in the construction phase that started in fiscal 2017 we carried out design and manufacturing. In fiscal 2020, we had been building a pilot demonstration carrier in order to verify loading/unloading and transportation technologies to transport liquefied hydrogen derived from brown-coal in Australia to Japan.

2 Challenges facing the pilot demonstration carrier

The design and manufacturing of ships to transport liquefied gases must comply with the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (commonly known as the IGC Code[1)]) adopted by the International Maritime Organization (IMO). But while the current IGC Code applies to gases such as liquefied petroleum gas (LPG) and LNG, it does not apply to liquefied hydrogen. For this reason, the IMO issued interim recommendations [2] for Japan-Australia marine transportation of liquefied hydrogen by approving a Japan-Australia joint proposal. In addition, based on the interim recommendations, and by setting more specific requirements on each of the items, Nippon Kaiji Kyokai (ClassNK) issued Guidelines for Liquefied Hydrogen Carriers [3] to expand on the concepts involved in liquid hydrogen transportation and the requirements against various incident scenarios. We will ensure a high level of safety by complying with this guideline as well.

Figure 1 is a rendering of the completed pilot demonstration carrier. The shape of the hull is based on a coastal LNG carrier that we built before, and it is equipped with a cargo tank specialized for liquefied hydrogen. As liquefied hydrogen can be gasified by heat ingress more easily than LNG and may cause massive thermal shrinkage of the structure due to its cryogenic temperature, we have issues to resolve before we can put a liquefied hydrogen carrier into practical use.

(1) Cargo containment system (CCS)

Regulations require that the pressure and temperature of the cargo containment system (CCS) be controlled to counteract heat ingress. When accumulating the boil-off gas produced by heat ingress instead of releasing it to outside of the CCS, safe voyage to the destination must be ensured while maintaining the pressure. Also, heat ingress through the wall of the tank, pipes and the structure supporting the CCS from the outside must be minimized.

In addition, the CCS must be structurally intact to withstand the dynamic loads due to the ship's motion during a voyage.

(2) Cargo piping

Cargo piping requires high level thermal insulation in order to restrain the decline in transportation efficiency caused by gasification of the liquefied hydrogen on board, eliminate the formation of a high-density oxygen atmosphere generated by air liquefaction on the surface of the pipes, and eliminate any risk of damage to the carrier's structure from liquefied air droplets.

In addition, as the piping is affected by tremendous stress by thermal expansion and shrinkage while liquefied hydrogen is being loaded, and unlike on-land piping, by hull deformation, it must be protected from these.

(3) Cargo equipment

Liquefied hydrogen is very low temperature, 90°C lower than LNG, which means that it requires cargo equipment with greater thermal-insulation performance than cargo equipment used for LNG. Durability against hydrogen's physical properties must be confirmed and the appropriate materials must be selected in terms of high thermal-insulation performance and the prevention of hydrogen leaks.

3 Development design and element technology

(1) CCS

CCS adopts a horizontal-cylinder pressure vessel that does not form part of the hull. This corresponds to a Type C tank complying with pressure vessel standards defined in the IGC Code and ClassNK Rules and Guidance for the Survey and Construction of Steel Ships [4]. The pilot demonstration carrier can install two 1,250 m^3 CCSs, one of which is installed in the foreside.

(i) CCS thermal insulation system

A CCS for liquefied hydrogen requires thermal insulation performance that is approximately ten times

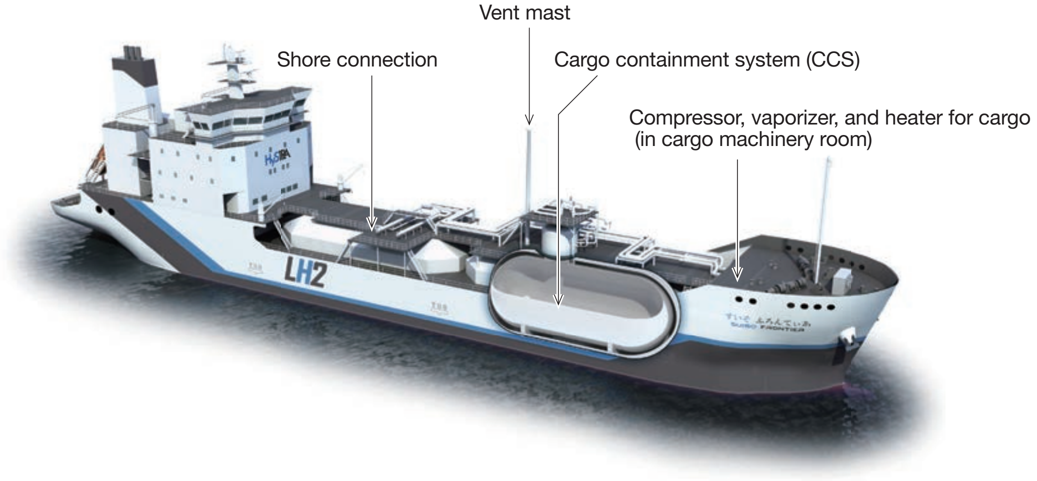

Fig. 1 Pilot demonstration carrier

higher than that for LNG. There are three modes of heat transfer, namely convection, conduction, and radiation. In order to reduce heat ingress from the surface of the CCS by heat convection and conduction, we adopted a double-shell structure consisting of inner vessel and outer shell, as shown in **Fig. 2**.

The supporting structure connecting the inner vessel and outer shell, the pipes, and the measuring instruments are a path of heat ingress by heat conduction. As a measure to reduce this, we adopted materials with low heat conductivity, lessened the cross-sectional area of its structural materials, and made conduction paths longer. As a method to reduce heat radiation, we apply the double-shell vacuum insulation system with multi-layered insulation which is a metalized laminated film with high reflectivity. We designed the CCS with sufficient margin to handle the temperature and pressure increase within the CCS on a normal voyage, which enabled a Japan-Australia voyage without releasing any boil-off gas to outside the CCS. Even when the inner vessel is full of liquefied hydrogen, the surface of the outer shell is kept at an atmospheric temperature, generating neither liquefied atmosphere nor liquefied nitrogen.

In addition, as a tool to ensure a safe voyage during transportation, the CCS is equipped with a Vacuum Insulation Performance Deterioration Monitoring System (VIPDM). Its purpose is to maintain the thermal insulation performance and confirm the safety of a voyage by continuously monitoring the deterioration rate of vacuum and predicting any risk of thermal insulation performance deteriorating too quickly.

(ii) CCS support structure

For the inner vessel and outer shell of the CCS, we adopted austenite stainless steels, a material suitable for use in cryogenic conditions. The support structure, which stably holds the inner vessel on the outer shell without letting them touch each other due to the ship motion during the voyage, cause more heat ingress, especially by heat conduction. So, to support the inner vessel we adopted a saddle structure made with glass fiber reinforced plastics (GFRP), which have excellent thermal insulation properties and strength. We studied various properties of the GFRP support structure in vacuum and cryogenic temperature conditions, such as strength, heat conduction, and outgas, and designed them to have the required durability throughout the lifetime of the CCS.

The inside of the CCS is at an atmospheric temperature during construction and regular inspections, but it is at a cryogenic temperature when fully loaded. The temperature distribution inside of the CCS is even affected by the liquid level of the ballast and by loading and unloading. The inner vessel shrinks and expands in line with temperature changes, while the outer shell remains at an atmospheric temperature and thus the temperature difference between the inner and outer shell causes a relative displacement. For this reason, we designed it to have a structure in which two circular-arc saddle structures installed at the front and back of the inner vessel support it, and the saddles absorb the relative displacement by sliding on the inner surface of the outer vessel.

(iii) Tank dome

As the relative displacement between the inner vessel and outer shell due to temperature difference is large, we installed all pipes penetrating the CCS into a tank dome placed at the top part of CCS. In the tank dome, we placed cargo piping, conduit pipes, and an access hole.

(iv) CCS manufacturing technology

Kawasaki has been manufacturing spherical liquefied hydrogen storage tanks for rocket launch facilities as well as on-land liquefied hydrogen storage tanks and double-hull

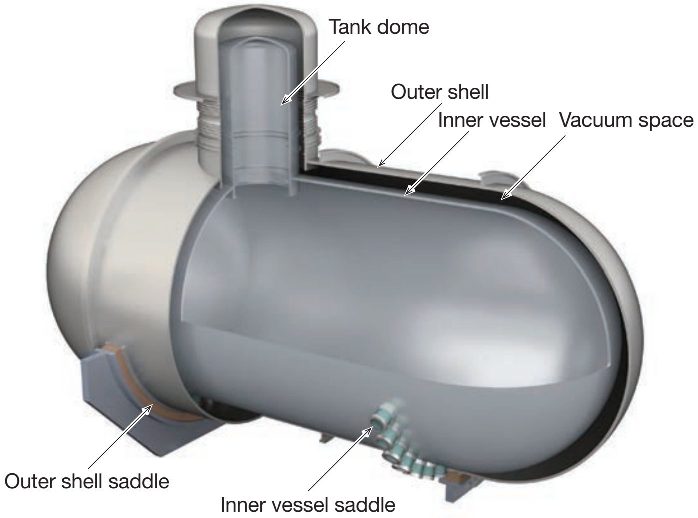

Fig. 2 CCS's double-shell structure

vacuum thermal insulation tanks for trailers. We have also manufactured a large-sized LNG storage tanks for ship. We manufactured the CCS by combining such technologies.

(2) Double-wall vacuum insulated piping

We adopted the double-wall vacuum insulation system for the cargo piping, similar to the CCS, to ensure high thermal insulation performance. The inner pipe must be stably supported by the outer pipe without letting them touch each other. Due to thermal expansion and shrinkage, the inner and outer pipes become different in length. So, based on the double-wall vacuum pipe specifications we applied to on-land hydrogen facilities before, we kept the thermal expansion and shrinkage during loading and unloading and the carrier's static/dynamic displacement in mind as we developed a double-wall vacuum pipe for ships. For the valves for cryogenic use, we adopted vacuum long bonnet valves with jackets, which have high thermal insulation performance.

(3) Cargo equipment

To ensure the durability of the cargo equipment against the physical properties of hydrogen, based on marine equipment practically proven for LNG carriers and on-land equipment proven for hydrogen, we reviewed all materials and specifications to cope with the properties of hydrogen and the on-board utilization environment. For key equipment, we conducted tests using liquefied hydrogen in the development phase, carried out operational risk assessment, and took measures for identified issues.

To enhance the thermal insulation properties and reduce the risk of leaks, we adopted bayonet joints, as shown in **Fig. 3**, for the shore connection that connects to the loading arm system (LAS) of the loading/unloading terminal. Bayonet joints are commonly used as thermal-insulated joints for liquefied hydrogen. Other cargo handling equipment includes a compressor to compress hydrogen gas, an evaporator to gasify liquefied hydrogen, and a heater to warm cryogenic hydrogen gas.

4 Building and demonstration

We started designing and manufacturing the CCS in fiscal 2017, started building the carrier hull in January 2019, and launched the carrier in December 2019 (**Fig. 4**).

(1) Carrier hull

An outline of the pilot demonstration carrier, such as key dimensions, is shown in **Table 1**. As the carrier uses CCS of pressure vessel, we do not have to dispose of boil-off gas onboard during the voyage. We employed a diesel-electric propulsion system in which three main diesel generators supply electric power to two propulsion motors and a propeller is driven through a reduction gear. The hull is equipped with a bow thruster, a schilling rudder (a rudder with high lift force and wide rudder angle), and a four-blade controllable pitch propeller to improve operability when berthing and unberthing.

(2) CCS

The inside of the CCS (**Fig. 5**), which was completed in March 2020, is equipped with submerged motor-driven pumps, a pipe support for fixing pipes, and equipment to efficiently cool the inside of the CCS.

(3) Demonstration test

We will move to the demonstration phase after the liquefied hydrogen carrier is completed in 2020. In Phase I

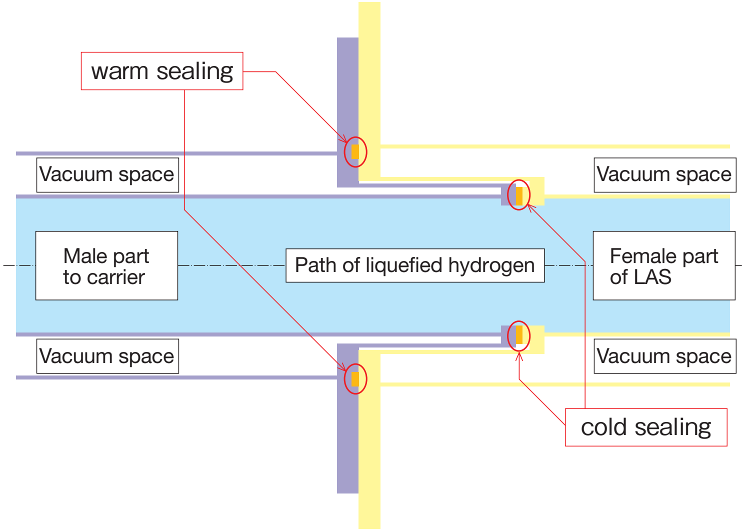

Fig. 3 Bayonet joint

Fig. 4 Launching ceremony of pilot demonstration carrier

Table 1 Outline of pilot demonstration carrier

Key dimensions	Overall length〔m〕	116
	Width〔m〕	19
	Depth〔m〕	10. 6
Gross tonnage		approx. 8, 000
Propulsion system		Diesel-electric propulsion
Navigation speed〔knots〕		approx. 13
Endurance〔nautical miles〕		approx. 11, 300
Maximum allowed persons onboard〔number of persons〕		25
Ship's registry/Classification		Japan/ClassNK

Fig. 5 Cargo containment system (CCS)

of the demonstration, for the purpose of verifying the functions, performance, and safety of the CCS, piping, and cargo equipment of the carrier, we will conduct each of the following test items in the storing and loading/unloading terminal that was constructed in the northeast area of Kobe Airport Island, which is located off the coast of Kobe City:

- Gas replacement in the CCS (efficient gas replacement method)
- Cool down of the CCS (efficient CCS cooling method)
- Loading of cargo liquid (filling the CCS with liquefied hydrogen from the terminal)
- Operation of the cargo pump (operation under cryogenic conditions)
- Operation of other cargo equipment (function and performance)
- Confirmation of thermal insulation properties (thermal insulation performance of the CCS and pipes)
- Full load test (full load cruising and unloading procedure)

In Phase II, we will demonstrate fully loaded marine transportation between Japan and Australia.

Conclusion

In the pilot demonstration, we will demonstrate the loading and unloading of liquefied hydrogen and verify the CCS's thermal insulation and storage performance at sea, aiming at the establishment of technologies for future mass transportation. We will also proceed with the development of a larger liquefied hydrogen carrier.

Last of all, we have been conducting this demonstration project as part of 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. We would like to express our sincere gratitude and appreciation for their support.

References

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