Study on Modern Hydrogen Carrier Technology

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Abstract. Hydrogen is a promising energy with high efficiency and zero pollution, but the low energy density makes it challenging to transport hydrogen efficiently and safely over long distances. Characteristics of liquid hydrogen bring difficulties to transportation system design. The low temperature and hydrogen embrittlement affect the design of the storage tank. The evaporation rate of liquid hydrogen makes it necessary to install an insulation system. The harsh working environment also affects the structure design. As large-scale transportation plays an important role in international energy trading, this article delves into the properties of liquid hydrogen. The storage and insulation technology are summarized. By comparing the characteristics of liquid hydrogen and LNG, according to the commonalities and differences between the two, the design of key systems of liquid hydrogen in storage, and container insulation technology has been analyzed. This article may provide a theoretical guide for the development of liquid hydrogen carriers.

Keywords: Liquid Hydrogen; Carrier; Research; Storage technology.

1. Introduction

A hydrogen carrier refers to a cargo ship that is used to transport and store hydrogen. When the distance between the liquid hydrogen(LH2) production plant and the user is relatively long, the ship transportation of LH2 becomes an efficient and economical mode of transportation, which has many advantages such as low cost, large cargo volume, and remote transportation. It is one of the new trends of hydrogen energy redistribution in the world.

Since hydrogen is a kind of gas with low energy density, it is challenging to transport hydrogen efficiently and safely over long distances. For the cargo containment system of liquid hydrogen carriers, certain characteristics of hydrogen, such as the low temperature of -253°C and hydrogen embrittlement, affect the design of the storage tank. In addition, the evaporation rate of liquid hydrogen is much higher than liquid natural gas(LNG), it is very important for the LH2 carrier to carry out the research on the LH2 insulation system. For the possible phenomenon of thermal expansion and contraction in the low-temperature environment, the tank support system should also be taken into consideration. Hydrogen carriers need to offer solutions to overcome these challenges.

Currently, the development of hydrogen carriers is still in preliminary stage. The world's first ocean-going LH2 carrier “Suiso Frontier” is built in 2021 and after about 3.5 weeks of sailing, the first batch of hydrogen from Australia successfully arrives in Japan[1,2]. This is the world's first long-distance maritime transport of LH2.

As large-scale transportation plays an important role in international energy trading, this article delves into the properties of LH2. The storage and insulation technology are summarized. By comparing the characteristics of LH2 and LNG, according to the commonalities and differences between the two, the design of key systems of LH2 in storage, and container insulation technology has been analyzed. This article may offer a reference for the development of LH2 carriers.

2. Hydrogen Storage Technology

2.1. Traditional hydrogen storage methods

Nowadays, several types of hydrogen storage methods have been developed. The most common type is compressed hydrogen gas. The hydrogen is stored under high pressure in gas cylinders or

tanks. Another type is LH2. Hydrogen is cooled to extremely low temperatures and liquefied for transportation and storage.

In addition to compressed and LH2, there are alternative hydrogen storage methods such as metal hydrides and hydrogen-rich chemicals. Metal hydrides can absorb and release hydrogen, allowing for more accessible storage and transportation. Hydrogen-rich chemicals, such as ammonia or methylcyclohexane, can be used as the storage medium[3].

The choice of hydrogen storage method depends on factors such as storage capacity, energy density, safety, and infrastructure availability. Research and development in this field aim to improve the efficiency and practicality of hydrogen transportation, enabling the widespread use of hydrogen as a clean energy source.

2.2. Liquid organic hydrogen carrier

Many aspects of LH2 carrier design may get experiences from LNG carriers. However, LH2 carriers have different characteristics. At present, most of the storage tanks of LNG carriers use metal tanks combined with an insulation layer to store LNG. Compared with the temperature of LNG(-163°C), the low temperature of LH2(-253°C) brings challenges to the existing LNG insulation technology. As LH2 is sensitive to heat, it is required that the heat efficiency of latent heat entering the spherical tank must be reduced to 1/10 of LNG, which is not higher than 0.01%/ day evaporation rate[4].

A promising way of hydrogen storage is the liquid organic hydrogen carrier (LOHC). LOHC is a technology that uses liquid organic matter to realize hydrogen storage and transportation through the reversible process of hydrogenation and dehydrogenation without destroying the main structure of organic matter. The organic matters studied by researchers include cycloalkanes, polycycloalkanes, carbazole, n-heterocyclic, and so on. LOHC hydrogenation is an exothermic reaction and dehydrogenation is a strong endothermic reaction. Common organic hydrogen storage media include cyclohexane, methylcyclohexane, naphthalene, n-ethyl carbazole, dibenzyltoluene, and dimethylindole [5]. The main research direction of German Hydrogenious Company is dibenzyl toluene, which has progressed to the application demonstration stage. The main research direction of Chiyoda Chemical Construction Company in Japan is methylcyclohexane, which has been used for ocean-going hydrogen transport[6].

3. LH2 container insulation technology

To design a hydrogen container, the main problem that should be considered is cold insulation. The commonly used passive insulation technologies are shown as follows:

3.1. Stack insulation technology

The surface of the LH2 storage tank is coated with a certain thickness of thermal insulation materials to achieve the purpose of thermal insulation. The common coating materials include powder type, fiber type, and solid foam type. The advantages of this technology are low cost and good applicability to irregular tank shapes. However, as the technology is relatively simple, the thermal insulation performance is inferior to other passive thermal insulation technologies[7].

3.2. High vacuum insulation technology

Through the improvement of the storage tank body, a double-wall interlayer is used as an adiabatic space. The pressure in the space is required to remain below 1.33×10^{-3}Pa[7]. This design eliminates the effect of gas thermal conductivity and gas convection heat transfer on the temperature of the goods in the tank.

3.3. Vacuum powder insulation technology

The principle of vacuum powder insulation technology is to fill the insulated space of the storage tank with insulation materials and pump to a certain vacuum for insulation protection of the tank. The commonly used filling materials are mostly porous insulation materials and the pressure is about 1 ~10 Pa. This technology is a combination of stacked insulation and vacuum insulation type.

3.4. High vacuum multi-layer insulation technology

In the vacuum-insulated space of the tank, the material with low thermal conductivity is arranged parallel to the cold wall radiation screen. This technology has good thermal insulation performance with lightweight. However, the manufacturing cost is high, the process is more complicated, and the adaptability to the complex shape of the tank is poor.

3.5. High vacuum multi-screen insulation

A new type of thermal insulation structure is produced by the combination of multi-layer thermal insulation technology and steam cold screen, achieving excellent thermal insulation performance. In addition, this technology is generally suitable for small storage vessels of LH2 and liquid nitrogen.

4. Feasibility of hydrogen carriers

Transporting hydrogen overseas is significantly different from LNG and other fuels. Unlike the mature international oil and LNG trade, the volume-energy density of hydrogen is low, and transoceanic hydrogen transportation is very challenging, requiring a high mass-energy density and volume-energy density to meet the economic requirements of long-distance transportation. At present, the technologies suitable for transoceanic hydrogen transportation mainly include hydrogen liquefaction, LOHC, and ammonia. Hydrogen liquefaction is done by physical cooling, while LOHC and ammonia combine hydrogen into larger molecules by chemical methods, making it easier to transport in liquid form. LOHC and ammonia are often not used as final products directly, and hydrogen gas needs to be regenerated by chemical methods after reaching the destination. Among the three transoceanic storage and transportation technologies for hydrogen, LOHC and ammonia have more comprehensive advantages than LH2.

For LH2 carriers, the most important problem is the insulation system. If a high-performance insulation and support system can be developed, a 200,000m^3 LH2 carrier can be built using mature very large vessel construction technology.

As there are obvious evaporation losses in these operations, the technical requirements of loading and unloading operations, including the design of vaults and pipelines, should be comprehensively considered.

For the basic design elements of hydrogen storage tank carriers (hull form, power system, overall layout, hull structure design), conventional technologies of LNG carriers can be used for reference. The density of LH2 is much less than LNG, so the requirement for the strength of the hull structure is not too high. As there are many special safety requirements, a unified design concept and standard based on the risk analysis of hydrogen leakage accidents, accidental failures, collisions, and strandings is needed[8].

5. Future prospects of hydrogen carriers

5.1. Design of large hydrogen carrier

In the conceptual design phase of the LH2 carrier, the following important design requirements need to be focused on the following aspects:

5.1.1. Storage tank loading capacity

As a 1000 MW power station consumes 1200t of LH2 per day, taking into account transport losses, the required tank loading capacity is about 14000t. For a 200,000m^3 carrier, if a round trip is 20 days, two carriers need to be loaded and transported every 10 days[9].

5.1.2. The number of storage tanks

Considering the influence of tank layout on the balance of the transport ship during navigation, the assembly of pipelines and the stability of broken tanks, four storage tanks can be used to form the storage system for the spherical tank transport ship, and two storage tanks can be used to form the storage system for the diamond tank transport ship.

5.1.3. Durability and ship speed

The shipping distance is about 6,000 nautical miles. It can sail 6,000 nautical miles every 10 days at a speed of 20 knots to 25 knots.

5.1.4. Type of ship

Considering the required ship speed, a standard single-hull carrier is feasible.

5.1.5. Vaporization rate

It can be envisaged that hydrogen-fueled engines will be used in the future. Similar to liquefied natural gas vessels that use evaporated natural gas, the hydrogen produced by the evaporation of LH2 can also be recovered and used as fuel for the engine.

5.2. The possibility of hydrogen-powered ship

The hydrogen-powered ship is an important project for clean energy transportation. The research results show the advantages of this propulsion system, such as high thermal efficiency and zero CO_2 emission, making this propulsion system suitable for the future, specifically for hydrogen carrier ships[10, 11]. The following reasons show that the suggested propulsion system is feasible to apply in terms of the technical aspect.

1) A combined cycle gas turbine fueled by hydrogen achieves 55% thermal efficiency with zero CO2 -emission advantage, as the conventional fuel reaches 54.5%.

2) The simulation results show that the combined cycle gas turbine fueled by hydrogen has an acceptable thermal efficiency and power output performance to be a successful propulsion system with 6% of degradation at different weather conditions.

6. Conclusion

According to the characteristics of hydrogen, in this article, the design and research of key systems are carried out, and the design concepts of the cargo system, safety system, and other key systems are completed.

This article points out the low temperature and high-pressure conditions of LH2 storage, and introduces the current storage technology of hydrogen transport and the advantages and disadvantages of LOHC compared with traditional methods. Five common passive insulation techniques are introduced. These are important technical means for LH2 carriers to ensure cargo safety and reduce BOG.

By comparison with LNG carriers, it is pointed out that LH2 has a low volume energy density and needs a high-performance thermal insulation support system. Due to many special safety requirements, a unified design concept and standard based on hydrogen leakage accident and accidental failure risk analysis are needed.

Based on the basic ship type of the cargo carrier ship, the overall design of the LH2 carrier ship is given, including loading capacity, the number of storage tanks, durability and ship speed, type of ship, and vaporization rate.

Although the hydrogen propulsion system has the advantage of zero-emission, it still has the problems of high cost and low safety. The hybrid power system based on hydrogen storage and fuel cell technology has great application potential in the field of ocean engineering, but the promotion and application on ships still need more attention to related issues.

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