Demonstration Tests of Three Types of Liquid Hydrogen (LH_2) Vaporizers

Yasutake MIWA*1・Tomohiro SUZUKI*1・Shinji EGASHIRA*1・Masataka AZUMA*1・Yoshihiko TSURU*1・Takumi NISHIMURA*1

*1 Compressor & Static Equipment Engineering Department, Compressor & Static Equipment Unit, Machinery Business

Abstract

Kobe Steel owns multiple types of liquefied natural gas (LNG) vaporizers to suit various applications and is developing liquid hydrogen (LH_2) vaporizers based on the design and manufacturing techniques the company has cultivated over many years. Liquid hydrogen is stored at −253℃ and must be processed at a temperature approximately 100℃ lower than LNG, posing great technical challenges for a heat exchanger. Therefore, reliability should be secured by conducting actual liquid demonstration tests to back up performance and thermal stress calculations. To this end, a small demonstration machine has been prototyped to conduct demonstration tests using liquid hydrogen. This paper describes the current status of demonstration tests of three types of vaporizers with different characteristics: an intermediate-medium vaporizer (IFV), an open rack vaporizer (ORV), and a microchannel heat exchanger (DCHE).

Introduction

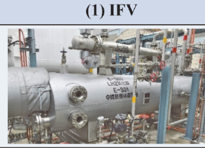
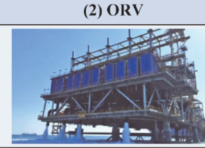
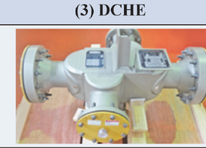
Kobe Steel has supplied many LNG (liquefied natural gas) vaporizers, a market in which we are a leading manufacturer, of various types and for various applications all around the world. Amidst this, plans have emerged in recent years to import and utilize liquid hydrogen (LH_2) as part of industry efforts to achieve net-zero carbon emissions by 2050.

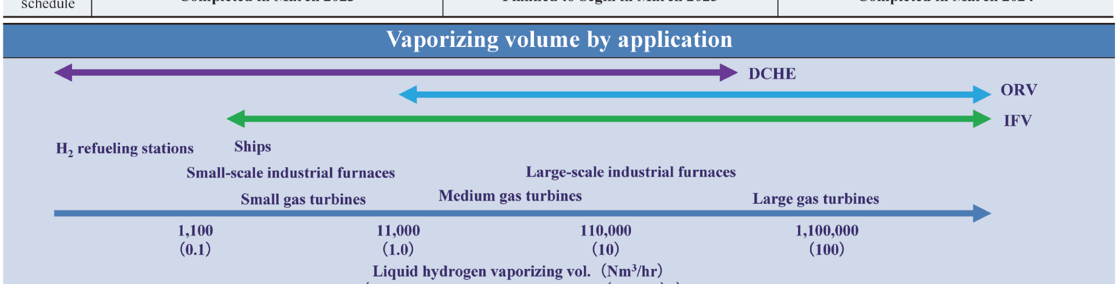
LH_2 is stored at -253℃ and has a processing temperature that is approximately 100℃ lower than that of LNG, posing great technical challenges for the heat exchanger. Therefore, it is necessary to create a small LH_2 vaporizer demonstration unit as a prototype, conduct demonstration tests using LH_2 to collect heat transfer performance and mechanical data on the vaporizer, and lay the foundation for scaling up.

Table 1 shows the features, intended applications, and demonstration test schedule overview for each of three types of LH_2 vaporizers: intermediate fluid vaporizer (IFV), open rack vaporizer (ORV), and microchannel heat exchanger (diffusion-bonded compact heat exchanger, DCHE).

This paper outlines the results of demonstration testing for these three types of vaporizers and future development plans.

Table 1 Liquid hydrogen vaporizer product lineup

Liquid hydrogen vaporizer product lineup			
Type	(1) IFV	(2) ORV	(3) DCHE
Appearance			
Features	Material: Stainless steel, titanium (for seawater) ● Eliminates the risk of freezing seawater and industrial water by using propane as an intermediate fluid. Suitable for mid- to large-scale vaporizers. ● Enables the use of exhaust heat from nearby facilities. ● Enables the use of cold energy through the secondary use of heating medium (wide temp. range)	Material: Aluminum alloy + thermal spray ● Uses seawater as heating medium, making it an economic solution for mid- to large-scale vaporizers ● Seawater is an open system, making it difficult to use cold energy ● Allows for the transition of an LNG power plant to a hydrogen co-firing plant using existing seawater intake/outlet facilities as is	Material: Stainless steel ● Enables downsizing while maintaining high thermal fatigue strength. ● Uses brine as heating medium. ● Enables the use of cold energy through the secondary use of heating medium (narrow temp. range)
Demo. schedule	Completed in March 2023	Planned to begin in March 2025	Completed in March 2024



1. Developing a large-capacity liquid hydrogen vaporizer (IFV), which supports the use of cold energy

1.1 Choosing the large-capacity (IFV), which supports the use of cold energy

Plans are in place to conduct demonstration tests of hydrogen co-firing and pure hydrogen firing in gas turbines. These tests, which will foster the commercialization of hydrogen power generation by 2030, require LH_2 vaporizers with a capacity of approximately 30,000 to 50,000 Nm^3/hr. Furthermore, improving energy efficiency is critical for the stable supply of hydrogen. Utilizing the cold energy from LH_2 for purposes such as increasing gas turbine efficiency through intake air cooling could contribute to this objective.[1), 2)] The IFV is the optimal choice for this purpose given its proven track record among LNG vaporizers and its capacity to support large-scale, continuous, and stable vaporization for cold energy utilization.

1.2 Structure and vaporization process of the IFV

The IFV uses a heat source such as seawater and an intermediate fluid such as propane to vaporize cryogenic liquids.

Fig. 1 shows a conceptual diagram of the IFV. LH_2 enters the heat transfer tubes of the LH_2 vaporizer (E-2). It then undergoes heat transfer with the intermediate gas in the upper part of the intermediate fluid vaporizer (E-1) shell. Nearly all the LH_2 vaporizes and travels to the shell side of the H_2 heater (E-3) via connecting piping. Here, heat transfer with seawater flowing through the heat transfer tubes heats the hydrogen gas for discharge at ambient temperature. Meanwhile, the intermediate fluid condenses on the outside of the heat transfer tubes of the E-2 due to heat transfer with LH_2 and falls to the lower part of the E-1 shell. The seawater flowing inside the E-1 heat transfer tubes transfers heat to the intermediate liquid, causing the gas to vaporize again and then vaporize the LH_2 in the heat transfer tubes of the E-2. Unlike ORVs, in which the heat source is vented to atmosphere during vaporization, IFVs can circulate the heat source in a closed loop. This enables effective extraction of cold energy using the cooled intermediate fluid or heat source fluid.[3)]

1.3 Challenges of using IFVs for LH_2

Because no company had pursued LH_2 vaporization in IFVs, the associated practical challenges were not yet known. Therefore, we created a small cold energy recovery-type LH_2 vaporizer demonstration unit as a prototype and conducted demonstration tests to collect heat transfer performance and mechanical data, laying the foundation for scaling up the vaporizer.

Fig. 2 shows the demonstration IFV. The E-3 heat exchanger is mounted on top of the E-1 shell to save space. The E-1 shell has a sight glass for checking the status of the intermediate fluid. The outside of the E-2 has a strain gauge and a thermocouple. We constructed dedicated equipment for the IFV at Kobe Steel's Takasago Works for the demonstration of LH_2 vaporization. **Fig. 3** shows the process flow of this facility. The heat source is circulating water. An electric heater was used as a simulated load for temperature control during testing. **Fig. 4** shows a photo of the entire facility.

This demonstration unit was designed for a performance rating of 0.1 ton/h (1,200 Nm^3/h) to correspond to the smallest size at which heat transfer performance could be verified. The mechanical design of the unit conforms to the Designated Equipment Inspection requirements of the High Pressure Gas Safety Act. After undergoing the

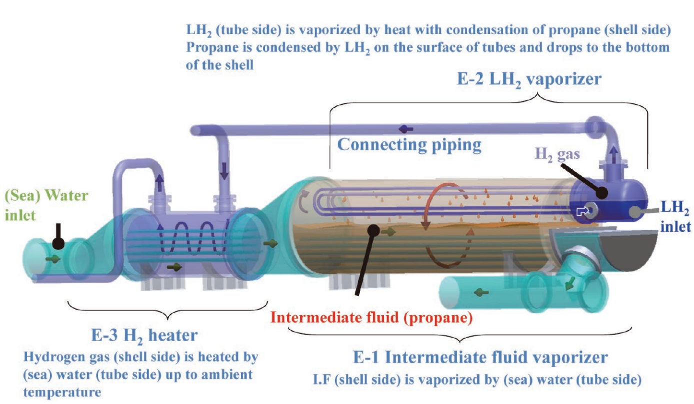


Fig. 1 Schematic of IFV

Fig. 2 Outside view of IFV for LH_2 vaporization demonstration

inspections prescribed by The High Pressure Gas Safety Institute of Japan, it received a passing test certificate.

The four points below were confirmed or investigated during the demonstration of LH_2 vaporization.

(1) Even during continuous operation, the temperature of the vaporized gas at the outlet does not decrease, allowing for stable vaporization of LH_2.
(2) Even when LH_2 flows through inside the heat transfer tubes, the intermediate fluid (propane) outside the heat transfer tubes does not freeze.
(3) It is possible to extract stable cold energy for utilization.
(4) The stress and strain during actual operation were measured and compared with the results of thermal stress analysis.

1.4 Results of the demonstration test of LH_2 vaporization using the IFV

Table 2 shows the test conditions.

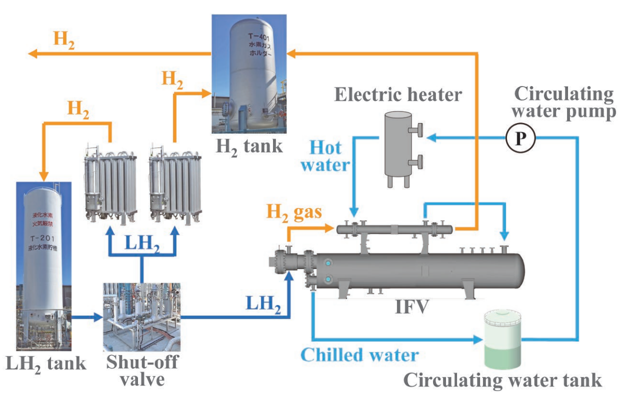


Fig. 3 Schematic flow of LH_2 vaporization demonstration facility

Fig. 4 Outside view of LH_2 vaporization demonstration facility

1.4.1 Confirming stable vaporization

The sample data in **Fig. 5** from the demonstration shows the trend in hydrogen outlet temperature and flow rate. Vaporized gas temperatures were stable for over one hour, demonstrating that LH_2 can undergo stable vaporization without a decrease in the temperature of the vaporized gas at the outlet even during continuous operation.

1.4.2 Testing for freezing of the intermediate fluid

The temperature of the LH_2 is below the freezing point of the intermediate fluid (propane). Therefore, there was concern that the intermediate fluid might freeze on the heat transfer tubes when LH_2 flows through them. However, visual inspection via the sight glass (**Fig. 6**) and the operating data confirm that even when LH_2 flows through inside the heat transfer tubes, the intermediate fluid (propane) outside the tubes does not freeze.

Table 2 Test conditions of IFV for LH_2 vaporization demonstration

Condition	Case 1	Case 2	Case 3	Case 4	Case 5
H_2 flow rate (Nm^3/h)	1,200	1,200	1,200	1,200	1,300
H_2 Press. (MPaG)	0.70	0.70	0.70	0.40	0.70
CW flow rate (m^3/h)	8.0	6.8	4.5	8.0	8.0
CW inlet Temp. (°C)	20	20	30	20	20
CW temp. Difference (°C)	Above 10	Above 15	Above 20	Above 10	Above 10

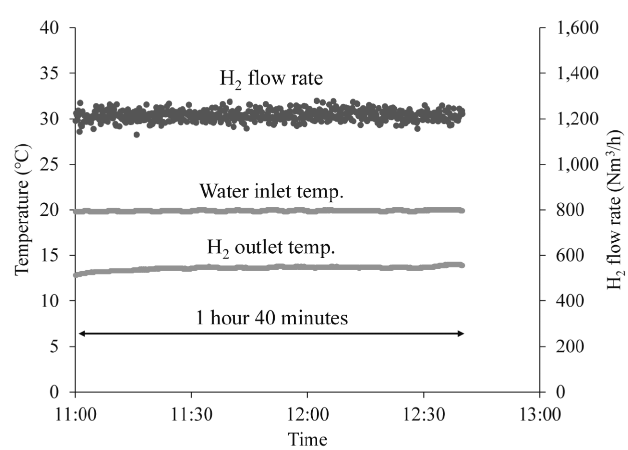


Fig. 5 Example of H_2 outlet temp. and H_2 flow rate trend during demonstration test

1.4.3 Confirming stable cold energy extraction

Fig. 7 shows the trend of the circulating water inlet and outlet temperatures upon fluctuation of the hydrogen flow rate. The circulating water is cooled via heat transfer with hydrogen gas and an intermediate fluid. It must be supplied at a stable temperature to ensure efficient cold energy utilization even during fluctuations in cooling load. This demonstration test confirmed that even with fluctuations in the hydrogen flow rate, it is possible to have a stable supply of chilled water at approximately 7℃, which is more than 10℃ cooler than the inlet water temperature of 20℃. This demonstrates that a stable supply of cold energy is possible.

1.4.4 Comparison of thermal stress analysis with stress-strain measurements during operation

High stresses are expected near the tube sheet of the E-2 because of the temperature differentials. As such, we compared finite element analysis (FEA) results from this region with the temperatures and stresses generated during rated operation. While this paper does not include detailed comparisons, the research by Egashira et al.[4)] shows that the stress-strain results correspond to the thermal stress analysis results qualitatively, validating the analysis method.

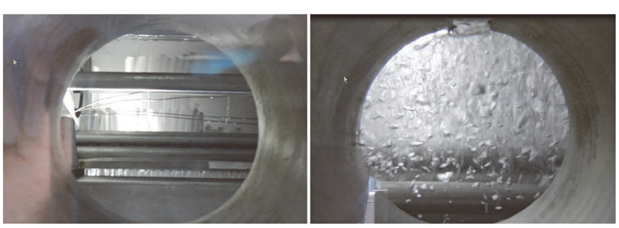


Fig. 6 Photo of propane boiling and condensing behavior from sight glass

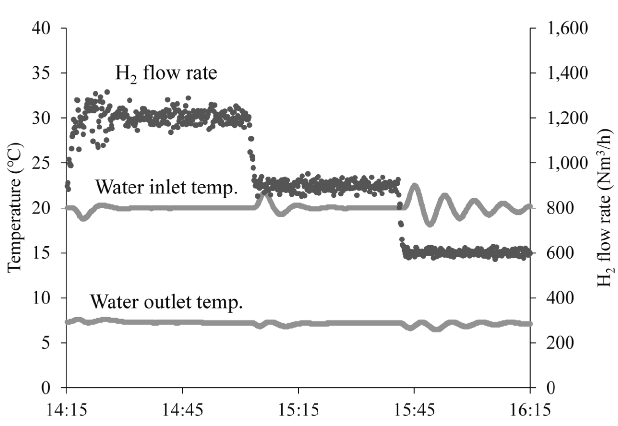


Fig. 7 Trend of water inlet and outlet temp. during H_2 flow rate fluctuation

1.5 Plan for demonstrating high-pressure LH_2 vaporization using IFV in hydrogen cogeneration system (CGS) of Kobe's Port Island

We collected operating data below the critical pressure of hydrogen during the demonstration test described in Section 1.4. The next step is to investigate the heat transfer behavior of the IFV at pressures above the critical pressure. Comparing this data with the data from below the critical pressure in the previous demonstration will reveal challenges across a wide range of operating pressures. For this operational demonstration, we incorporated the actual equipment into the hydrogen fuel supply system of the Kobe hydrogen CGS demonstration facility. The New Energy and Industrial Technology Development Organization (NEDO) selected this demonstration as a grant project in June 2023 to "improve the efficiency and performance of the hydrogen fuel supply system in a hydrogen CGS regional model." Demonstration testing commenced in fiscal year 2025.

2. Progress in large-capacity LH_2 vaporizers (ORVs)

2.1 ORVs, the most widely used large-capacity LNG vaporizer

ORV heat exchangers usually use seawater as a heat source to heat LNG from -160℃ to a temperature above 0℃. The ORV is a high-flow LNG vaporizer that uses economical, readily available seawater. As such, it is superior in terms of both operating and construction costs. Consequently, it is widely adopted as the large-capacity vaporizer at LNG terminals all over the world.

2.2 Structure and vaporization process of the ORV

Fig. 8 (left) shows the structure of the ORV and an overview of its process. This counterflow heat exchanger is characterized by a simple vaporization process and structure. Its heat transfer tubes are

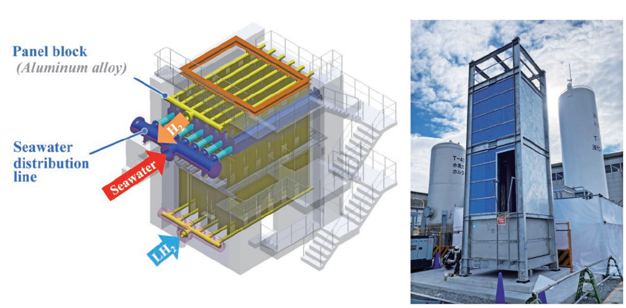


Fig. 8 The structure of ORV and outside view of ORV for LH_2 vaporization demonstration

arranged vertically. A low-temperature fluid (LNG) flows inside the tubes and a heating fluid (seawater or industrial water) flows from the outside. The heat transfer tubes are made of an aluminum alloy with excellent low-temperature toughness and heat transfer performance. Since corrosion by seawater is a concern for aluminum alloys, a material serving as a sacrificial anode is applied to the heat transfer tubes via thermal spraying.

2.3 Challenges of using ORVs for LH_2

The logic behind developing our new LH_2 vaporizer based on the structure of LNG ORVs was twofold. First, LH_2 vaporizers are expected to support large-scale, continuous, and stable operation; and second, we frequently receive inquiries regarding ORVs because they are a familiar technology. Kobe Steel had no empirical data on LH_2 vaporization in ORVs at the start of development, so there was uncertainty regarding the practical challenges. Therefore, we created a small demonstration unit as a prototype and conducted demonstration tests to collect heat transfer performance and mechanical data, laying the foundation for scaling up the vaporizer.

2.3.1 Heat transfer performance with LH_2

Vaporizing LH_2 requires the transfer of approximately five times more heat per unit mass than for LNG. Consequently, the same mass flow rate as LNG cannot be vaporized. Furthermore, if the heat transfer coefficient inside the tubes is the same as for LNG, a 100℃ decrease in operating temperature could promote ice formation and degrade performance. To apply the performance simulation used for LNG to LH_2, the actual heat transfer performance data of LH_2 as determined through testing must be incorporated into the simulation.

2.3.2 Thermal stress analysis for using LH_2

The operating temperature of LH_2 is around -250℃, which is about 100℃ colder than LNG's operating temperature of about -150℃. Managing the resulting increase in thermal stress is a key challenge. requiring cryogenic thermal stress analysis. Kobe Steel has many years of experience conducting thermal stress analysis for LNG vaporizers, including ORVs, and draws on this expertise to advance the development of ORVs for use with LH_2.

2.4 Plans for the demonstration test of LH_2 vaporization using the ORV

Kobe Steel already has a comprehensive facility for evaluating LH_2 vaporizer performance as part of our hybrid-type hydrogen gas supply system and has completed demonstration tests for IFVs below critical pressure. In fiscal year 2024, we expanded the facility to include a demonstration setup for an ORV for LH_2 (Fig. 8, right).

Starting in March 2025, we conducted demonstration tests using actual liquid hydrogen to collect data to perform thermal stress analysis and determine heat transfer performance, providing information critical to the challenges of ORV design. We then began working toward commercializing the LH_2 vaporizer.

This demonstration unit was designed for a performance rating of 0.1 ton/h (1,200 Nm^3/h) to correspond to the smallest size at which heat transfer performance could be verified. As with the IFV described above, this unit also received a passing test certificate for the Designated Equipment Inspection required by The High Pressure Gas Safety Institute of Japan.

The objective of demonstrating LH_2 vaporization is to confirm the two points below.

(1) Even during continuous operation, the level of the ice buildup outside the tubes stabilizes within an assumed standard range, and LH_2 vaporization remains stable without a decline in the outlet vaporized gas temperature.

(2) Thermal stress analysis based on the temperature distribution in the lower area of the ORV confirms sufficient thermal fatigue life.

3. Progress in small-capacity LH_2 vaporizers (DCHEs) for offshore applications

3.1 DCHEs, a compact and highly pressure-resistant vaporizer

The DCHE features a compact design and excellent pressure resistance, yielding a wide scope of application in space-constrained environments such as floating production storage and offloading systems (FPSO) and floating LNG (FLNG) production systems. Its application range has also expanded to LNG vaporizers for vessel fuel gas supply systems (FGSS). Kobe Steel has established technology to prevent the freezing of the heat transfer fluid using LNG and is deploying it for shipboard and land-based applications.

3.2 Structure and vaporization process of the DCHE

The DCHE is a compact heat exchanger whose main manufacturing processes include etching as well as diffusion bonding to simultaneously join the plates. **Fig. 9** (left) shows its structure.

The etching process involves dissolving metal using the corrosive action of chemicals such as etching solutions. This technique is applied to stainless steel plates to form millimeter-sized flow channels through which fluid passes.

Diffusion bonding involves stacking the processed plates and bonding them via diffusion at the atomic level at the joint interface. Since the base materials bond directly, the strength of the joint is equivalent to that of the base metal. The etching plates are stacked in a specific ratio, with some plates carrying LNG and others carrying a heat transfer fluid such as an ethylene glycol/water mixture, enabling direct heat transfer through the plates between adjacent flow channels. LNG and the ethylene glycol/water mixture are distributed to each plate in the stack via a header, which is downstream of a nozzle.

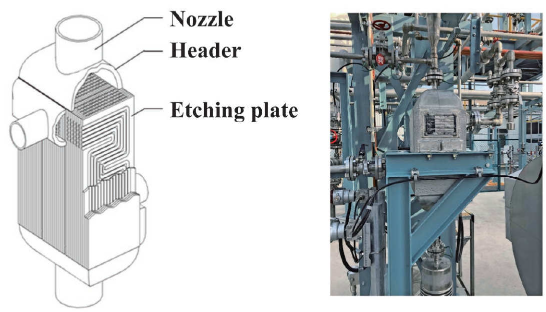


Fig. 9 Schematic structure of DCHE

3.3 Challenges of using DCHEs for LH_2

LH_2 is used at cryogenic temperatures far below the freezing point of the ethylene glycol/water mixture, the heat source. As such, a critical challenge is to prevent freezing in the flow channels of the heat exchanger. Although over 50 years of plate-fin heat exchanger design technology ensure solid heat transfer design, there are no calculations that can predict freezing phenomena. Therefore, we identified the conditions related to freezing under various operating states through experiments using LNG, liquid nitrogen (LN_2), water, and an ethylene glycol/water mixture. This led to the development and patenting of two unique anti-freezing technologies. **Figs.10** and **11** summarize the patents (“1 cold:3 hot design” and “2-zone design,”

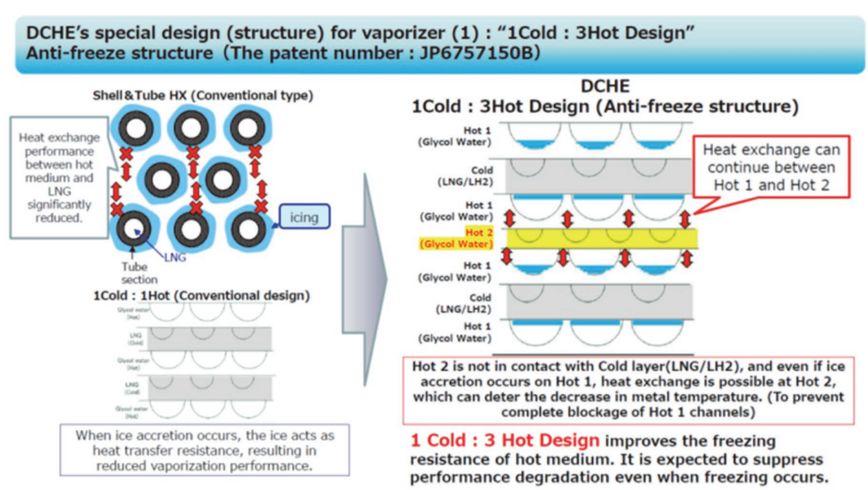


Fig.10 Anti-freeze structure (1 cold : 3 hot design)

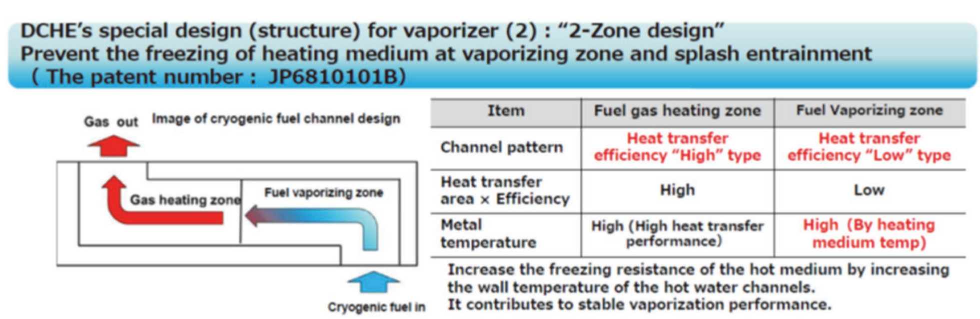


Fig.11 Anti-freeze structure (2 -zone design)

respectively).

Kobe Steel supplies LNG vaporizers for satellite bases, LNG fuel vaporizers for marine use, and high-pressure LH_2 vaporizers, which validates our design methodology and anti-freezing technology.

We needed to first confirm that the established technical standard applies at LH_2 temperatures (-253℃) below the critical pressure at which boiling phenomena occur. Therefore, we conducted a demonstration test using a prototype unit that simulated the size of the product to be delivered.

We used LH_2 for testing and installed the test unit in parallel with the IFV in the hybrid-type hydrogen gas supply system. **Table 3** and Fig. 9 (right) show the design specifications of the test unit, the test conditions, and a photo of the test unit. This test unit also received a passing test certificate for the Designated Equipment Inspection. The LH_2 vaporization demonstration confirmed the two points below.

(1) The heat transfer fluid does not freeze, and vaporization performance is stable.
(2) Heat transfer performance meets design specifications.

3.4 Results of the demonstration of LH_2 vaporization using the DCHE

3.4.1 Confirming heat transfer fluid freezing behavior and stable vaporization performance

If the heat transfer fluid freezes, the flow channels of the heat transfer fluid will gradually become obstructed, causing the pressure drop to gradually increase. Therefore, we ran the system in continuous operation at the design point (LH_2 flow rate 18.9 kg/h) for one hour to observe the change in pressure drop of the heat transfer fluid as an indicator of whether the heat transfer fluid froze.

Fig.12 shows that the pressure drop of the heat transfer fluid remained stable and did not trend upward, confirming that the heat transfer fluid did not freeze at the design point.

Table 3 DCHE specifications for hydrogen vaporization performance test

Basic specifications	Vaporization capacity (liquid hydrogen)	18.9 kg/h
	Type	Micro channel heat exchanger
	Material	Stainless steel type 316 L
Design specifications (path A) Fluid: liquid hydrogen	Inlet temp. (°C)	-253
	Outlet temp. (°C)	30
	Operating press. (MPaG)	0.3
Design specifications (path B) Fluid: ethylene glycol water	Inlet temp. (°C)	40
	Outlet temp. (°C)	35

Specifically, Fig. 12 shows the time-dependent changes in the flow rate of hydrogen, pressure drop of the heat transfer fluid (scale values not shown), and hydrogen gas outlet temperature.

The hydrogen gas outlet temperature was essentially constant over the one hour of continuous operation shown in Fig. 12, indicating stable vaporization performance.

3.4.2 Evaluating heat transfer performance

The following equation expresses the heat transfer rate Q of the heat exchanger.

$$Q = UA\Delta T$$

Where

Q : Heat transfer rate (kW)
U : Overall heat transfer coefficient (kW/(m²·℃))
A : Heat transfer area (m²)
ΔT : Logarithmic mean temperature difference (℃)

In this equation, when fluid properties and flow rates are similar, the overall heat transfer coefficient U is nearly the same. Furthermore, since the heat transfer area A is constant, UA indicates the performance of the heat exchanger. **Table 4** compares the UA calculated from the Q (heat transfer rate, kW) and ΔT (logarithmic mean temperature difference, ℃) measured

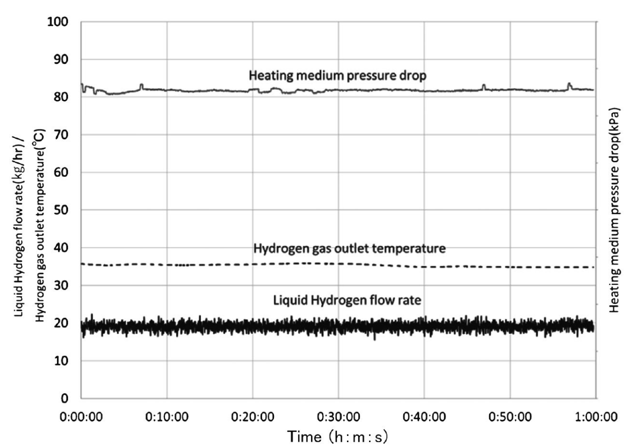


Fig.12 H_2 outlet temp., H_2 flow rate and heating medium pressure drop trend during performance test at design point

Table 4 Comparison of UA calculated from design value and actual test value

Item	Design	Actual measurements
Heat duty (kW)	23.0	25.3
Logarithmic mean temperature difference (°C)	69.5	40.2
UA (kW/°C)(*)	1	Over 1.5

(*) It is defined as 1 at the design point.

during performance testing with that of the design point. Since the *UA* calculated based on testing at the design point is at least 100% of the design value, testing confirms that the heat transfer performance meets the design specifications. These results demonstrate that the design of our LH_2 vaporizer, which uses the design criteria and patented technologies established for LNG vaporizers, is sound and that there is potential for commercialization.

Conclusions

This paper introduced the results and plans of demonstration tests conducted using the LH_2 supply facilities from the project "development of intermediate fluid vaporizer for liquid hydrogen that enables use of liquid hydrogen cold energy." This project, which received grant assistance from the New Energy and Industrial Technology Development Organization (NEDO), was completed at the end of March 2023. Upon completion of all demonstrations introduced in this paper, we will be able to offer an LH_2 vaporizer comparable to LNG vaporizers in our product lineup.

This research was made possible in part by the project "Development of Technologies for Realizing a Hydrogen Society" (JPNP14026), a grant program of the New Energy and Industrial Technology Development Organization (NEDO). We express our gratitude to NEDO and all involved.

Kobe Steel is advancing the societal implementation of hydrogen energy by supplying vaporizers capable of handling liquid hydrogen in various environments, from land-based to shipboard applications.

References

1) T. Komuro et al. Mitsubishi Heavy Industries Technical Review. 2010, Vol.47, No.4, pp.49-54.
2) T. Suzuki et al. R&D Kobe Steel Engineering Reports. 2020, Vol.70, No.1, pp.24-27.
3) S. Egashira. R&D Kobe Steel Engineering Reports. 2013, Vol.63, No.2, pp.33-36.
4) S. Egashira et al. Journal of High Pressure Institute of Japan. 2024, Vol.62, No.5, pp.2-12.