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KAWASAKI TECHNICAL REVIEW

Special Issue on Hydrogen Energy Supply Chain

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Kawasaki, Paving the way for a future hydrogen society .

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Special Issue on Hydrogen Energy Supply Chain

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Technological Development for Solving Social Issues

Hiroshi Nakatani
Director, Managing Executive Officer
General Manager, Corporate Technology Division

What is your policies regarding technological development?

Our vision for the future is based on our Group Vision 2030, in which we aim to achieve "Trustworthy Solutions for the Future." In line with this, we will continue to provide innovative solutions in a timely manner to an ever-changing society. Based on this vision, with the objective of solving various social issues, we are making proactive efforts toward developing technologies to expand our business into high value-added fields, such as market development and service-based businesses .

What is the role of the Corporate Technology Division?

The Corporate Technology Division is the research and development division of our headquarters. The Corporate Technology Division and business segments have integrated to develop products and services. Specialists in the Corporate Technology Division collaborate with engineers in the business segments starting from the planning stage to ensure the overall optimization of issues that involve contradicting factors. By matrix-type based operations like this, we are able to apply the knowledge we gained from past projects to other projects, and produce synergistic effects as a comprehensive heavy industry manufacturer that transcends business boundaries, such as through the development of motorcycles that integrate gas turbine technologies.

Furthermore, by envisioning the near future of our business segments, we propose products and services that solve the problems surrounding society and create technologies that will support future generations.

What are some business sectors you are focusing on for the future?

We are focusing on market development for new fields in the robotics business as a business opportunity to address social issues such as the declining birthrate and aging population, as well as the shrinking working population. In order to address the problem of our rapidly aging society and to respond to its needs, we will develop medical robots in cooperation with other companies to provide advanced medical care to as many patients as possible. To address the problem surrounding the decline in the working population, we are developing technologies to enable the use of robots in a wide range of fields, such as duAro, a robot that is capable of working in collaboration with humans, and Successor, a robot that learns and reproduces human skills.

In addition, we are currently working to provide services that offer added value by optimizing operations and maintenance tasks as our initial efforts to develop service-based businesses. Some examples of these efforts include our remote monitoring service for railroad tracks, which is currently under development for commercialization, and our remote monitoring system for gas turbines and gas engines, By combining hardware knowledge and digital technology, we aim to solve some of the issues we will face, such as labor shortages and environmental problems.

Furthermore, we are focusing our strengths on promoting the creation of a hydrogen-based society as a new business opportunity to solve the two problems of global warming and resource depletion in the future.

What is your efforts to achieve a hydrogen-based society?

Utilizing our proprietary cryogenic technology, which makes large-volume transportation of hydrogen possible by liquefying hydrogen, we began leading the way in efforts to achieve a hydrogen-based society about 10 years ago, ahead of our competitors. Specifically, we have been developing technologies and products that are used in each step along the hydrogen energy supply chain, which include production, transportation, storage, and utilization. To achieve a hydrogen-based society, we also need an environment where hydrogen energy can be widely used by everyone. To achieve this, it is important to establish standards and rules for handling hydrogen, and we are the leading company involved in the development of these standards and rules. We believe that establishing these rules will make it easier to use hydrogen energy around the world, and will also create opportunities and markets for our products and services to spread worldwide.

Closing comments

We believe that our various technological developments aimed at solving social issues will contribute to the sustainable management of our company. We will continue to make the utmost efforts in achieving our goals.

Development and Demonstration toward Hydrogen Energy Introduction Essential for Establishing a Decarbonized Society

Eiichi Harada
Executive Officer,
Deputy General Manager, Corporate Technology Division

Introduction

Kawasaki is the only company in the world who holds in a single company all the core technologies to produce, transport, store, and utilize hydrogen, which covers the entirety of a hydrogen energy supply chain. The history of these core technologies originated with liquefied natural gas (LNG) technology, in which we have accumulated numerous achievements over the past half century.

The need for such technologies, unique to us as a general heavy industrial company is increasing and those technologies are rapidly gathering momentum as people expect to prove to be useful for the global environment and the future of humankind. Hydrogen is a clean energy that emits no CO_2 when used, and it has been recognized as being essential for achieving the goal of the Paris Agreement, that is, net zero CO_2 emissions by the end of this century. In response to this, many countries are incorporating the utilization and supply of hydrogen into their policies.

We have been conducting research and development on the establishment of a hydrogen energy supply chain since fiscal 2010, and finally, in fiscal 2020, our first-in-the-world demonstration project is entering the operation phase. In addition, in order to achieve commercial operation in the early 2030s, we are continuing the development of technologies and are in the process of establishing a business entity.

1 Changes in environment and society

In 2005 the Kyoto Protocol became effective with the aim of creating a low carbon society. In 2015 the Paris Agreement was adopted, and after that, 187 countries and regions submitted their own goals to realize a decarbonized society. However, global environmental change is occurring faster than such changes in social environment, and CO_2 reduction is no longer just an environment issue but an urgent social issue.

The countries that signed the Paris Agreement have set their target for CO_2 reduction, and among them, Norway, Sweden, France, the UK, and others have legislated net zero emissions by 2050. Japan's target is an 80% reduction by 2050, and net zero emissions as soon as possible after 2050. To achieve such targets just by saving energy is obviously impossible, so continued introduction of renewable energies is indispensable.

However, Japan is already the leading country in terms of renewable energy introduction density, but it has challenges to overcome such as location and cost reduction whenever it expands its renewable energy generation facilities. **Figure 1** shows renewable energy density, which is calculated by dividing renewable energy generation by habitable land, the remainder of subtracting forest land from the land area of the entire nation. Japan's density is higher than Germany's, one of the leading countries in renewable energy introduction. Japan is also among the countries with the highest energy consumption density, as shown in **Fig. 2**, and it would be very constrained if it were to introduce and expand enough renewable energies in its limited national land to cover such high demand.

Given this background, a new zero-emission, less-expensive energy that is abundantly available and that contributes to the realization of a decarbonized society, which at the same time satisfies the criteria for selecting future sources of energy as defined by what is known as energy security, economic efficiency, environment, and safety (3E+S), is being sought after. The result is that the idea of converting less-expensive, unused resources and renewable energies in other countries into hydrogen, and transporting the hydrogen to Japan to make use of it has drawn attention.

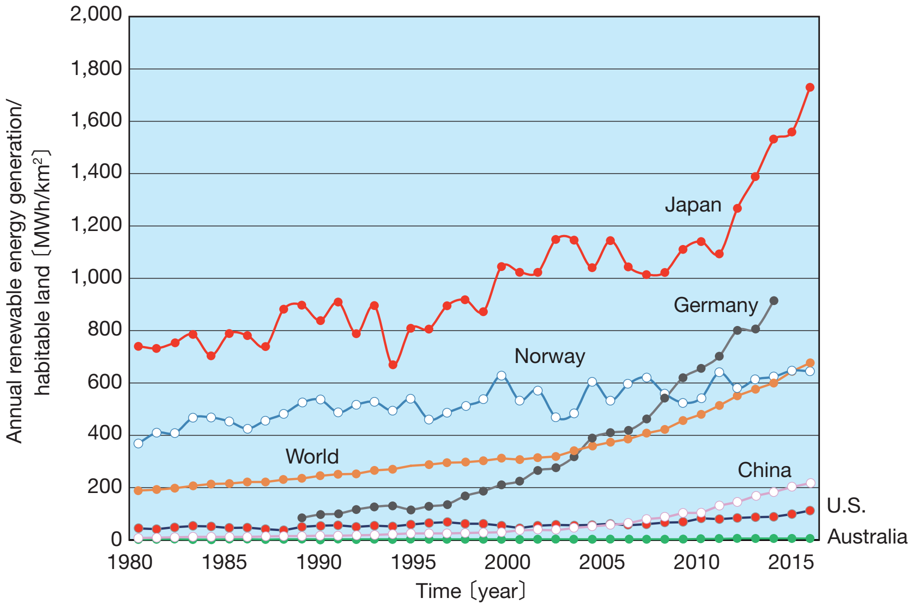

Fig. 1 Renewable energy density*

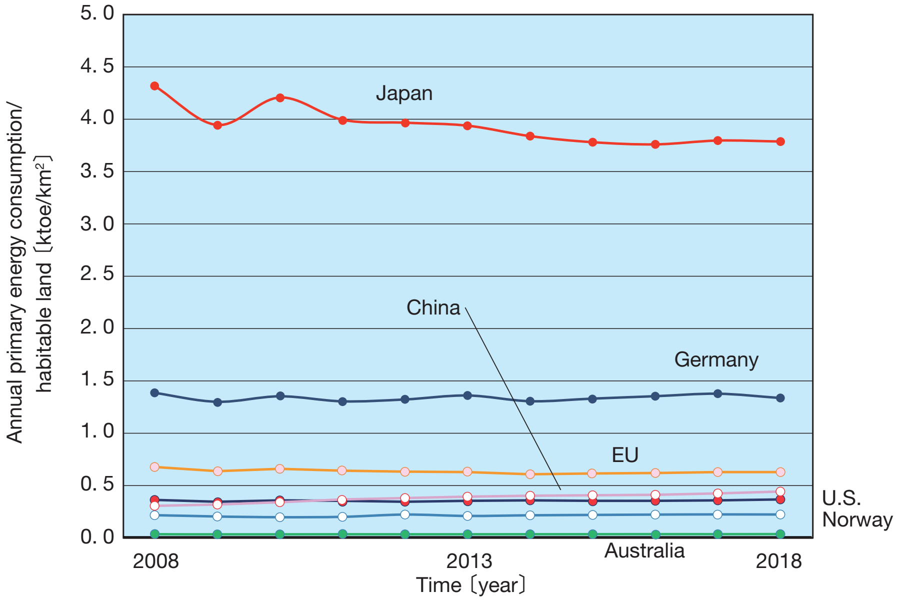

Fig. 2 Energy consumption density*

2 Japan's strategy on hydrogen

The Council for a Strategy for Hydrogen and Fuel Cells was established in December 2013 gathering experts from industry, government, and academia as part of an initiative by the Ministry of Economy, Trade and Industry. The council released the Strategic Roadmap for Hydrogen and Fuel Cells in June 2014. The roadmap was renewed in 2016 and 2019, and the latter clarifies the cost target for hydrogen and the performance target for key equipment and systems toward social implementation of hydrogen and fuel cells, and defines action plans to achieve these targets.

The Strategic Energy Plan, which is the basis of Japan's energy policy, starts covering hydrogen in its fourth edition released in April 2014. While hydrogen has been incorporated into the nation's policies in this way, in December 2017 the Basic Hydrogen Strategy was formulated and released through cross-ministerial cooperation. The strategy aims to commercialize hydrogen fueled power generation and a hydrogen energy supply chain early in the 2030s, and it presents a vision that the capacity of future hydrogen fueled power generation will reach 30 GW.

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* Data source: Website of US Energy Information Administration, and BP Statistical Review of World Energy (2019)

While promoting hydrogen policies ahead of the rest of the world, Japan hosted Hydrogen Energy Ministerial Meetings in Tokyo in September 2018 and 2019 attended by related ministers from around the world.

3 Global movement toward hydrogen utilization

Japan has been a leader in the utilization of hydrogen energy in the world, but in recent years, every country, both in the West and the East, is aiming to utilize hydrogen. One reason for this is the Hydrogen Council. The council was established in January 2017 by 13 major companies of various industries from around the world such as energy and resources, plants, industrial gas, and transportation machinery, and its aim is to promote hydrogen utilization toward a decarbonized society. The council, of which Kawasaki is a founding member, is expanding its scale with 92 companies as of the end of July 2020, including new members from the industries of fuel cells, trading, and banks.

Hydrogen Scaling Up, a report issued by the Hydrogen Council in November 2017, defines the following seven roles that hydrogen will play in terms of CO_2 reduction:

①Enables the mass introduction of renewable energy and hydrogen fueled power generation

②Enables energy accommodation and transportation between sectors and between regions

③Increases the flexibility of energy systems as a buffer

④Enables low carbonization in transportation

⑤Enables low carbonization in energy for industrial use

⑥Enables low carbonization in heat and electricity in buildings

⑦Enables the supply of low-carbon materials for industrial applications

The important thing here is that hydrogen is superior to a secondary battery in storage amount and duration, transportation range, and cross-sectoral accommodation ability, and has a far larger number of players who can engage in various hydrogen businesses such as hydrogen supply and utilization. This means that hydrogen's unique features could become a strong driving force for energy transition and bring benefits to both energy systems and end use. This report estimates that the economic effect of hydrogen in 2050 will be 2.5 trillion dollars and jobs for 30 million people (which are equivalent to the current number of jobs in the automobile industry) will be created. The report also encourages countries to refer to Japan's Strategic Roadmap for Hydrogen and Fuel Cells and formulate a roadmap tailored to their own situations. As a result, the U.S., EU, Australia, New Zealand, France, Germany, the Netherlands, Norway, Saudi Arabia, UAE, China, South Korea, and more have released or are formulating their roadmap.

Considering such global movement, some predict that a hydrogen-based society will come earlier than the previous forecast.

4 Establishment of hydrogen energy supply chain

The biggest challenge in hydrogen energy introduction is said to be cost and safety. To reduce cost, obtaining a large volume from inexpensive raw materials is effective and actually required. Considering this, we focused on brown-coal, which is a largely unused resource with abundant reserves in Australia. This inexpensive resource, for which there are no transactions with other countries, is used solely for local power generation, and its cost is a tenth that of coal.

In our project, a large amount of affordable hydrogen is stably produced from brown-coal, and by-product CO_2 is separated and captured, and then stored underground at the site (CCS: CO_2 Capture and Storage). This will enable the establishment of large-scale hydrogen supply infrastructure. In the future, we will realize the transition to a sustainable energy-based society by switching to hydrogen derived from inexpensive, foreign renewable energy.

When transporting hydrogen to Japan, long-range mass transportation will be in the form of liquefied hydrogen. Liquefied hydrogen has already been used for industrial applications and as rocket fuel for over half a century, and is a non-toxic, non-odorous, and global warming potential-free energy carrier conforming with requirements for a sustainable society. We regard liquefied hydrogen superior in sustainability above two other options being studied as energy carriers: ammonia, which is a deleterious substance, and organic hydride, which consumes energy to extract hydrogen.

As for safety, the other challenge in the introduction of hydrogen energy, as can be seen from the fact that hydrogen has a long history of use in numerous applications such as H2 rockets, industrial applications, fuel cell vehicles, hydrogen stations, and residential fuel cell appliances, we can use it safely, similar to other fuels, through understanding hydrogen's properties and handling it properly. To ensure perfect safety, we will continue to build up good results for mass utilization throughout the project, and demonstrate that hydrogen can be used safely in our daily lives.

As the door to commercialization, we are establishing a Japan-Australia pilot supply chain seamlessly running from start to end, as shown in **Fig. 3**. In 2016, Kawasaki, Iwatani

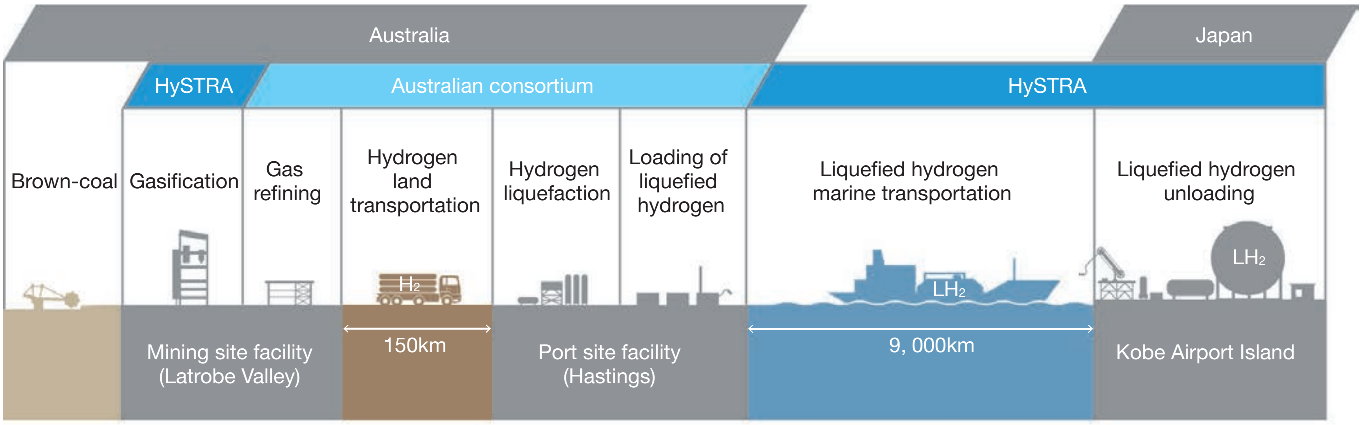


Fig. 3 Framework of Japan-Australia pilot supply chain

Corporation, Shell Japan Ltd., and Electric Power Development Co., Ltd. (J-POWER), came together to form the CO_2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA)—which was later joined by Marubeni Corporation, ENEOS Corporation, and Kawasaki Kisen Kaisha, Ltd.—and has been carrying out technology development to establish a hydrogen energy supply chain for the purpose of economical, stable procurement of a large amount of hydrogen with the support of the New Energy and Industrial Technology Development Organization (NEDO) (a grant project by NEDO called the Demonstration Project for Establishment of Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal). We are now commissioning a liquefied hydrogen carrier, a liquefied hydrogen unloading terminal in Kobe, and brown-coal gasification facilities in Australia.

Since Kawasaki, Iwatani, J-POWER, Marubeni, and AGL Loy Yang Pty Ltd formed a consortium in 2018, we have been constructing and commissioning gas refining facilities and a hydrogen liquefaction and loading terminal with a subsidy from the Australian government and the Victoria State government.

The construction of a liquefied hydrogen carrier and the facilities at each of the sites is well on track. In regard to our liquefied hydrogen carrier, a naming and launching ceremony was held in December 2019 (**Fig. 4**). The carrier was named SUISO FRONTIER and the ceremony was attended by 4,000 guests.

The governments of Japan and Australia cooperate in supporting the establishment of a hydrogen energy supply chain derived from brown-coal, and in a Japan-Australia summit meeting usually held at the end or beginning of the year, their cooperation on this project was announced in official documentation. The significant support for our consortium from the Australian federal and the Victoria State governments is part of that. In April 2018, a subsidy-awarding ceremony for this project was held in Latrobe Valley, where a brown-coal mining site is located. The construction of facilities is proceeding in Australia as well. These Japan-Australia pilot demonstrations have entered the operational phase that started in fiscal 2020.

Ahead of this, in fiscal 2018, as a grant project by NEDO, called the Smart Community Technology Development Project Utilizing Hydrogen Cogeneration Systems, under the coordination of Obayashi Corporation, in cooperation with Kobe City, the Kansai Electric Power Co., Inc., Iwatani Corporation, and others, Kawasaki successfully conducted a technological demonstration of gas turbine cogeneration, the key to hydrogen utilization, in a city area. We installed our 1 MW gas turbine (**Fig. 5**) on Kobe Port Island, and it successfully supplied heat and electricity to neighboring public facilities. This is the first time in the world that a hydrogen fueled gas turbine was operated in a city area.

As the proportion of renewable energy gets larger in the future, problems will be revealed, such as unstable power supply caused from fluctuating renewable energy sources and mismatches between electricity supply and demand. A way to solve this mismatch is power-to-gas technology, which is the idea of supplying surplus electricity generated from renewable energy to a water electrolysis, producing and storing hydrogen, and utilizing the stored hydrogen as energy.

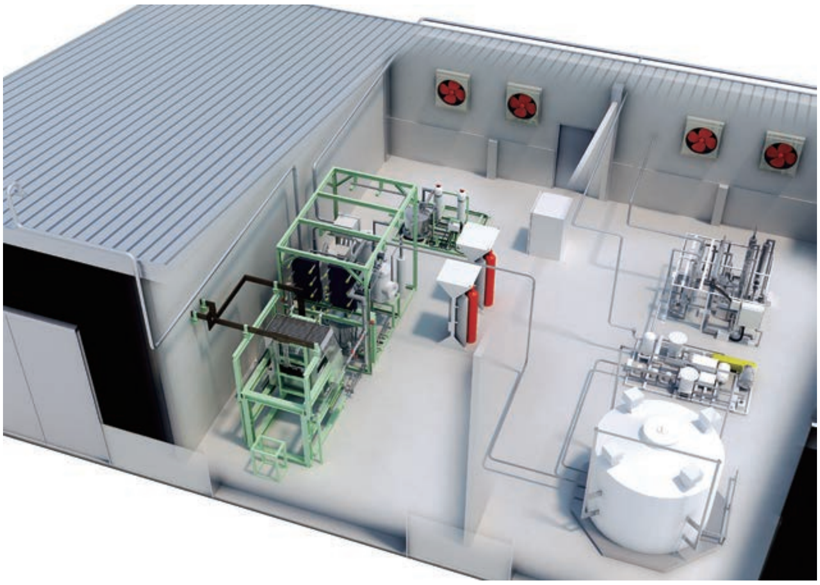
In 2018, under the coordination of Toyota Tsusho Corporation, Kawasaki conducted a power to gas demonstration commissioned by NEDO, called the Research and Development of Technologies for Stabilization, Storage and Use in Converting Unstable Electric Power Derived from Renewable Energies into Hydrogen in Hokkaido, in which we connected a water electrolysis system to a wind power generation facility in

Fig. 4 Launching ceremony of the liquefied hydrogen carrier SUISO FRONTIER

Fig. 5 Demonstration facility for hydrogen fueled gas turbine cogeneration (in Kobe City)

Tomamae, Hokkaido and successfully produced hydrogen. **Figure 6** shows the hydrogen production facilities. Such hydrogen derived from renewable energy is essential to establishing a sustainable energy-based society, and is needed to some extent even when considering the energy self-sufficiency rate. This technology will be important when hydrogen is produced using inexpensive renewable energies of other countries, which also offers hope that a large market will form.

(a) External appearance



(b) Equipment layout

Fig. 6 Wind-powered hydrogen production demonstration facility (Tomamae, Hokkaido, in 2018)

Conclusion

Kawasaki has been carrying out development projects for each phase in the realization of a hydrogen-based society, which includes the production, transport, storage, and utilization of hydrogen as actions based on the Sustainable Development Goals (SDGs). If we can utilize economical hydrogen derived from brown-coal to install infrastructure, and then switch to hydrogen derived from renewable energy, which is expected to have further cost reduction effects and a larger amount of production in the future, we will realize transition to a sustainable energy-based society.

By carrying out demonstrations toward future commercialization in a safe and steady manner, Kawasaki will facilitate hydrogen-related product development and commercialization to embody “KAWA-ru SAKI-e,” or “Changing forward” in English, exploiting the synergy of Kawasaki Group technologies, and move forward to become the top hydrogen manufacturer.

Technical Description

Activities for Realization of International Liquefied Hydrogen Energy Supply Chain

Major advanced countries have been implementing hydrogen energy to achieve a decarbonized society. Japan, as the top runner, aims to commercialize a CO_2*-free hydrogen energy supply chain, and starts operation of pilot demonstration project in 2020.*

In the pilot project, the following technical demonstrations are making progress: hydrogen production from brown-coal in Australia, hydrogen land transportation from the production site, loading onto liquefied hydrogen carrier, the world's first long-distance marine transportation of large-volume liquefied hydrogen and liquefied hydrogen loading/unloading technology at the Port Terminal in Kobe. Outcomes of the present project will be a basis for future hydrogen supply that can link every corner of the world to Japan.

Introduction

In recent years, disasters caused by extreme climate frequently strike countries around the world including Japan, and CO_2 emission reduction has become an urgent issue common to all humankind. Since the Paris Agreement has come into effect, the world is striving to achieve net zero CO_2 emissions by the end of this century. Concrete planning and actions are absolutely necessary to achieve this goal. As an essential technology for such concrete actions, renewable energy has been standing in the limelight, but it is becoming clear that as more renewable energy is introduced, it becomes more difficult to secure a stable supply of electricity. Hydrogen is drawing attention as a clean energy because it can compensate for this disadvantage and contribute to energy security and environmental issues, and at the same time, can provide almost the same level of convenience as fossil fuels.

1 Background

(1) Japan's hydrogen strategies

The Strategic Roadmap for Hydrogen and Fuel Cells 1), a conglomeration of the knowledge of industry, academia, and government, was developed and released by Japan's Agency for Natural Resources and Energy in 2014, earlier than COP21 where the Paris Agreement was proposed. In addition, as a result of cross-ministerial collaboration, the Basic Hydrogen Strategy 2) specifies the roadmap further and was approved by Japan's Ministerial Council on Renewable Energy, Hydrogen and Related Issues in December 2017. Also, the fifth edition of Japan's Strategic Energy Plan, which was released in July 2018, has specific descriptions on hydrogen energy utilization 3).

Japan's target for CO_2 emission is a 26% reduction in fiscal 2030 from the fiscal 2013 level, and the Japanese Cabinet also decided on the long-term target of an 80% reduction by 2050 and a 100% reduction as quickly as possible after that. To achieve such ambitious goals, transition to low carbon energy is needed, and it is thought that hydrogen will play an especially important role in the energy transition.

Japan's Basic Hydrogen Strategy looks at hydrogen as a key future energy option on par with renewable energy, and promotes hydrogen utilization in every sector including transportation, electric power generation, industry, buildings and households. According to the strategy, the commercialization of hydrogen fueled power generation and the establishment of a liquefied hydrogen energy supply chain to support it will start in the early 2030s. With this in mind, we have been conducting technology development and demonstrations.

Japan has been leading the world in activities for such hydrogen energy utilization, but in recent years, more countries, both in the East and the West, are pursuing hydrogen utilization.

(2) Followers around the world

Hydrogen energy utilization is gathering momentum all over the world. The Hydrogen Council[4], which was established in January 2017 by 13 global companies from areas such as energy and resources, plants, industrial gases, and transportation equipment, aims to achieve a hydrogen-based society as quickly as possible and has 92 member companies as of the end of July in 2020, increasing by a factor of six times in the four years since its foundation. In addition, 70% of G20 countries have incorporated hydrogen utilization into their policies. In this way, there is a rapidly growing likelihood of realizing hydrogen utilization and its market expansion.

2 Concept of a CO_2-free hydrogen energy supply chain

We made our Concept of a CO_2-free Hydrogen Energy Supply Chain (CO_2-free Hydrogen Chains) public in our Medium-Term Business Plan in 2010, and ever since, we have been working on technology demonstrations toward commercialization and the establishment of a cooperative consortium as well as technology and product development to achieve that .

Figure 1 shows the concept of CO_2-free Hydrogen Chains in which hydrogen is produced by gasifying and refining brown-coal in Latrobe Valley, Victoria State, Australia, liquefied and then shipped to Japan in a liquefied hydrogen carrier. Brown-coal is low in transport efficiency due to its high moisture content and the spontaneous ignition that can occur when it dries. Because of this, it has only been used locally for power generation in the vicinity of the mine. Half of all the coal reserves in the world are brown-coal. Among them, Victoria State in Australia has a vast amount of those reserves, and the brown-coal reserves in the Latrobe Valley area alone are equivalent to 240 years' worth of electric power generation in Japan. The Loy Yang Coal Field shown in **Fig. 2**, which is said to be the

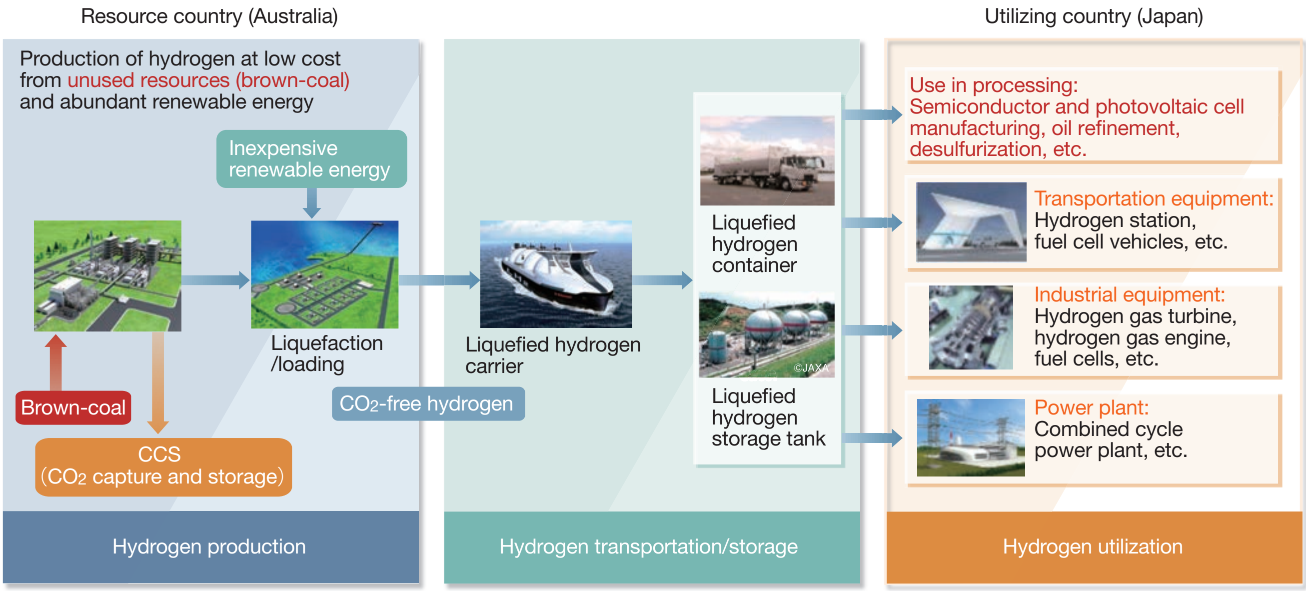


Fig. 1 Concept of CO_2-free Hydrogen Energy Supply Chains

Fig. 2 Loy Yang Coalfield in Latrobe Valley, Australia

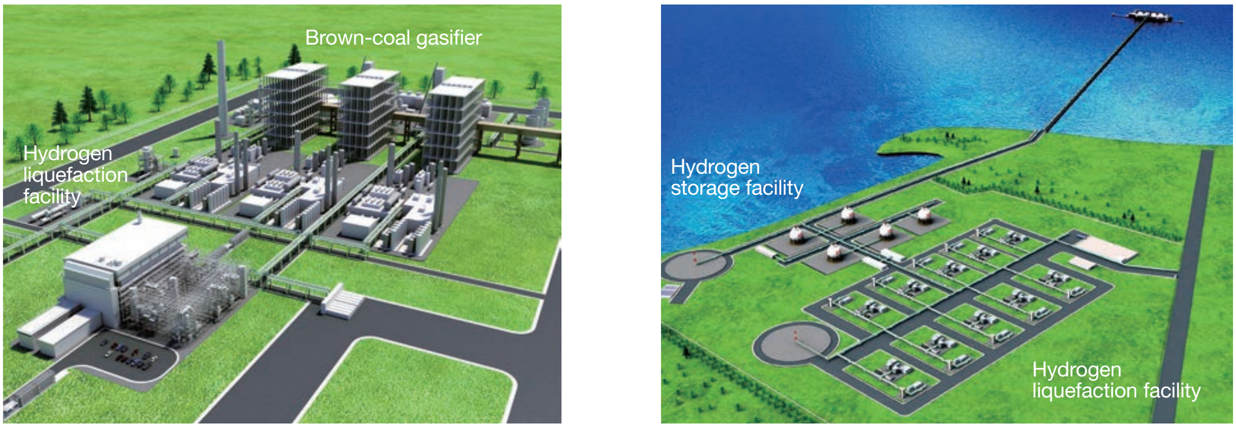
largest in the Southern Hemisphere, is an open-cut mine that boasts an astounding 14 km perimeter.

Hydrogen can be produced by gasifying and refining any fossil fuel, not just brown-coal, but in the refining process CO_2 is coproduced as well. By implementing carbon dioxide capture and storage (CCS) to capture the CO_2 byproduct at the site and store it underground, hydrogen can be obtained without releasing any CO_2 into the atmosphere (CO_2-free hydrogen). The Australian federal and the Victoria State governments are collaborating on a CCS project called CarbonNet, which makes Victoria State a good place to put both brown-coal and CCS to use [5]. The hydrogen produced in Latrobe Valley is compressed and transported through gas pipelines, and then liquefied in a hydrogen liquefier installed near a port. After being stored in a storage tank, the liquefied hydrogen is loaded onto a liquefied hydrogen carrier and shipped to Japan. This scale is equal to the liquefied natural gas (LNG) chain commercialized in the 1960s.

In order to evaluate the basic feasibility of this concept, we conducted conceptual design based on commercialization with the specifications shown in **Table 1** and the core facilities shown in **Fig. 3**, and evaluated economic efficiency by estimating the cost of equipment and

Table 1 Specifications of the CO_2-free Hydrogen Energy Supply Chain

Brown-coal consumption 〔Mton/year〕		4. 74
Hydrogen production	Oil equivalent 〔Mtoe/year〕	0. 764
	Volume 〔GNm^3/year〕	2. 51
	Weight 〔ton/year〕	225, 500
CO_2 storage 〔Mton/year〕		4. 39
Liquefied hydrogen carrier		Two 160, 000 m^3 carriers



(a) Hydrogen production site

(b) Hydrogen liquefaction/loading site

(c) Liquefied hydrogen carrier (160,000 m^3 capacity)

Fig. 3 Core facilities of CO_2-free Hydrogen Energy Supply Chains

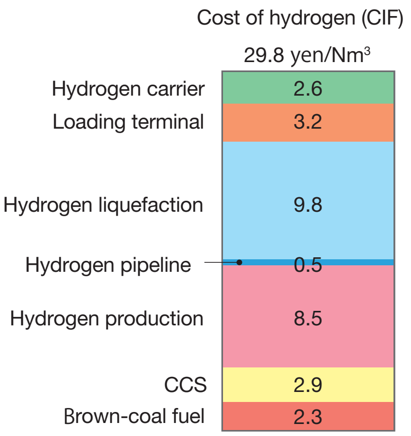


Fig. 4 Cost structure of CO_2-free hydrogen

operation. The commercialized hydrogen supply is equivalent to the amount consumed by three million fuel cell vehicles or a single one-million-kilowatt hydrogen gas turbine combined cycle power plant. As shown in **Fig. 4**, the Cost Insurance and Freight (CIF) for delivery to Japan was estimated to be approximately 30 yen/Nm^3 (334 yen/kg), of which the costs of raw brown-coal and CCS account for approximately 17%.

The CO_2-free Hydrogen Chains concept has the following features:

- Stable, large volume supply: hydrogen production from unused resources
- Good for the environment: on-site capturing and storing of CO_2 byproduct
- Enhance industrial competitiveness: technological and industrial ability sufficient for handling hydrogen required
- Restrain outflow of national wealth: does not result in just purchasing expensive resources

As you can see from the above, CO_2-free hydrogen meets the conditions required for future energy, that is, energy security, economic efficiency, environment and safety (3E+S).

This economic efficiency evaluation was conducted as an international project of the New Energy and Industrial Technology Development Organization (NEDO) and the outcomes have been recognized by both the Australian and Japanese governments.

3 Kawasaki's development of core technologies and products

In order to realize CO_2-free Hydrogen Chains, we need to make it "ready-to-use." The core technologies and products to produce, transport, store, and utilize hydrogen must be available to seamlessly operate from the beginning to the end of the supply chain. If even a single core product is missing, the supply chain will be interrupted and we will not be able to say we have put hydrogen into practical use. In addition, if a foreign product is needed anywhere in the supply chain, extra efforts and cost will be required to conform to standards and specifications.

"Ready-to-use" means the state in which not only the necessary technologies and products exist but also the rules and regulations required for operation and safety have been established. This is why technology development and rule establishment must proceed at the same time to realize the world's first CO_2-free Hydrogen Chain. Additionally, we must acquire intellectual properties at the same time to do business from an advantageous position. Therefore, we have been collaborating with stakeholders to work on technology development and the establishment of rules and standards for a liquefied hydrogen carrier, a loading arm for liquefied hydrogen, and so on.

One of our strengths in realizing a hydrogen energy supply chain is our technologies related to cryogenic liquefied gas that we have cultivated for many years, such as LNG carriers and the liquefied hydrogen storage tank and supply facilities at the Tanegashima Space Center. There are many different ways to carry hydrogen such as liquefied hydrogen and putting it in tanks, compressing hydrogen and putting it in gas canisters, and using absorbing alloys or organic compound media, but among them, liquefied hydrogen is already at the level of commercialization and is suitable for large-volume transportation and storage, and, it does not need any energy to convert it into ready-to-use hydrogen gas. Liquefied hydrogen is 70.8 kg/m^3 in density, lower than the 443 kg/m^3 of LNG, but has high volumetric efficiency. Specifically, it is approximately 800 times higher than atmospheric-pressure hydrogen gas. Also, it has a boiling point of 20.3 K, approximately 90 K lower than the 112 K of LNG, and low latent heat per volume, which requires high-efficiency liquefaction technology and high-performance insulation technology.

Major advantages of liquefied hydrogen are as follows:

- Already in practical use as transport media for industrial use and rocket fuel
- Highly efficient transport because no additional weight needs to be transported as it is not absorbed into or combined with any transport media such as metals and organic solvents
- Able to be evaporated at normal temperature on-site (energy is not needed)
- Once gasified, it is able to be supplied to a fuel cell without having to be refined, due to its high purity
- Able to be liquefied using less-expensive local energy when the supply site is located in an energy rich foreign country
- Able to contribute to cold energy power generation and

other purposes on-site by using the cold energy produced, because the energy when liquefied is not lost but converted into cold energy (-253°C)

- Clean and sustainable as it is non-toxic and has zero global warming potential (GWP)

We have been developing hydrogen technologies and products for its production, liquefaction, transportation, storage, and utilization, while advancing our cryogenic technology.

4 Progress of the project

To implement hydrogen energy in our society, all the core technologies from the supply side to the demand side should be seamlessly developed and linked, just like LNG. We have thus been engaged in hydrogen supply from overseas as part of the Japan-Australia pilot demonstration projects and in hydrogen utilization as part of the hydrogen gas turbine cogeneration demonstration project.

(1) Japan-Australia pilot demonstration projects

Toward the implementation of hydrogen energy in our society, we started conducting hydrogen energy supply chain technology demonstrations (Japan-Australia pilot demonstration projects) on a pilot scale (approximately 1/120 of commercial scale by carrier capacity) in fiscal 2020, including the world's first long-distance large-volume marine transportation of liquefied hydrogen produced from brown-coal-derived hydrogen. As shown in **Fig. 5**, this pilot project covers the whole hydrogen energy supply chain from the brown-coal gasification and hydrogen refining facility in Latrobe Valley through to the liquefied hydrogen unloading terminal at Kobe Airport Island, and will identify issues in technology, safety, operation, and social acceptance. It consists of the NEDO portion, which is a NEDO grant project called the Demonstration Project for Establishment of Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal, and the Australian portion, which is a grant project by Australian federal and Victorian state governments.

The NEDO portion is being conducted under the initiative of the CO_2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA), which was established in 2016 and is headed by us. The HySTRA's members are: Kawasaki Heavy Industries, Ltd., Iwatani Corporation, Electric Power Development Co., Ltd. (J-POWER), Shell Japan Ltd., Marubeni Corporation, ENEOS Corporation, and Kawasaki Kisen Kaisha, Ltd.

The Australian portion is conducted where Hydrogen Engineering Australia Pty Ltd (HEA), Kawasaki's subsidiary, serves as the main contact to the Australian governments. The participants are: Kawasaki, Iwatani, J-POWER and its subsidiary J-Power Latrobe Valley Pty Ltd (JPLV), Marubeni, AGL Loy Yang Pty Ltd, and Sumitomo Corporation.

In Japan-Australia pilot demonstration projects, Kawasaki is responsible for project coordination and the development and supply of technologies and device systems in each process.

(i) Gasification and gas refining

Figure 6 shows the brown-coal gasification and hydrogen refining facility. We delivered the following to JPLV: a preprocess facility to dehumidify and pulverize brown-coal to prepare it to be sent to a gasifier, and a facility to compress refined gaseous hydrogen and load it into land transport container trailers for delivery.

(ii) Liquefaction of hydrogen and loading of liquefied hydrogen

A site to liquefy high-pressure gaseous hydrogen has been constructed at the Port of Hastings. The liquefied hydrogen is loaded into container trailers made by Kawasaki, carried to the pier, and then loaded into a liquefied hydrogen carrier. **Figure 7** shows the hydrogen liquefaction terminal.

(iii) Liquefied hydrogen carrier

As a liquefied hydrogen carrier had never been built

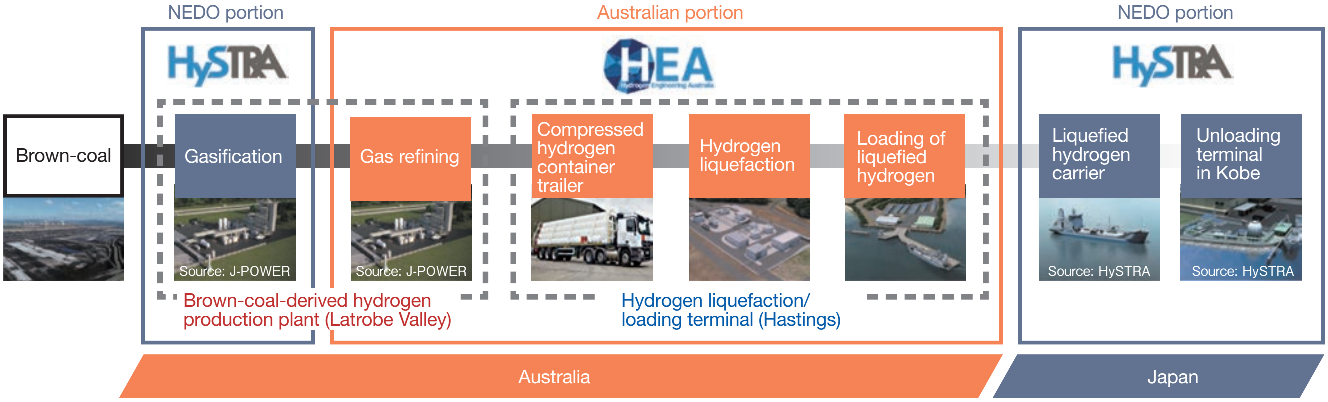


Fig. 5 The whole structure of Japan-Australia pilot demonstration projects

Source: HySTRA

Fig. 6 Brown-coal gasification and hydrogen refining facility (February 2020)

Fig. 7 Hydrogen liquefaction terminal at the Port of Hastings

anywhere in the world, we designed one based on the IGC Code of the International Maritime Organization (IMO), namely, the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk, which applies to LNG ships.

At the end of 2013, approval, in principle, was provided from Class NK for the cargo containment system installed in the liquefied hydrogen carrier (pilot demonstration carrier) for the Japan-Australia pilot demonstration projects. To get this approval, we proposed requirements for hull, materials, safety standards, and so on, taking account of the properties of liquefied hydrogen, as well as IGC code. Also, we conducted risk assessment by HAZID analysis.

To operate this liquefied hydrogen carrier, maritime authorities of Japan and Australia started discussions on safety standards in 2014, and the IMO approved interim recommendations for carriage of liquefied hydrogen in bulk in November 2016, which were a joint proposal by the two countries 6). This became a steady step toward the realization of large-volume marine transportation of liquefied hydrogen.

The pilot demonstration carrier has a vacuum insulated storage tank (1,250 m^3 in capacity) with a pressure-accumulation cylinder structure, which can store boil-off gas internally, like a coastal LNG carrier. After the basic design was completed in fiscal 2016, then detail design was conducted and construction began. The naming and launching ceremony took place at Kobe Works in December 2019. The storage tank was installed into the carrier in March 2020, it was outfit as shown in **Fig. 8**, and the operation started in the fall of 2020.

(iv) Kobe unloading terminal

Constructing and operating a liquefied hydrogen loading/unloading terminal for bulk carriers will also be a

Fig. 8 Liquefied hydrogen carrier under outfitting (May 2020)

world's first, just like the liquefied hydrogen carrier. We are constructing an unloading terminal in an approximately 100 ha area rented from Kobe City in the northeast part of Kobe Airport Island. **Figure 9** shows how the terminal.

The onshore liquefied hydrogen storage tank has a 2,500 m^3 capacity, which is the largest in Japan. The world's first loading arm system (LAS) for liquefied hydrogen adopts the method of suspending a stainless-steel double-wall vacuum flexible hose from a trellis frame. The tip of the LAS is equipped with an emergency release system to safely block liquefied hydrogen leaks when a carrier leaves the port in an emergency.

The terminal construction was completed in May 2020, and after some test runs, full operation of the terminal started in the fall of 2020.

(2) Hydrogen gas turbine cogeneration demonstration project

We conducted technology development and demonstration of a new energy management system (EMS) on Port Island in Kobe City, which aims to efficiently use electricity, heat and hydrogen energy on a community level by using a heat and electricity supply system (hydrogen cogeneration system) which has a 1 MW-class gas turbine fueled by hydrogen and natural gas at its core. Obayashi Corporation served as the project organizer of the NEDO grant project, called the Smart Community Technology Development Project Utilizing Hydrogen Cogeneration Systems, and installed and operated an integrated EMS and a heat supply system, and Kawasaki delivered a hydrogen cogeneration system. This was a joint project by Kobe City, the Kansai Electric Power Co., Inc., Iwatani Corporation, Kanden Energy Solution Co., Inc., and Osaka University.

One of the pieces of equipment used in this technology demonstration is shown in **Fig. 10**. The facility is installed in an urban area, and it supplied heat and electricity to neighboring public facilities, namely, an international exhibition hall, a sports center, a central city hospital, and a sewage treatment plant. The operation of a 100% hydrogen-fueled gas turbine cogeneration system installed in a city area was a first-ever attempt in the world, and

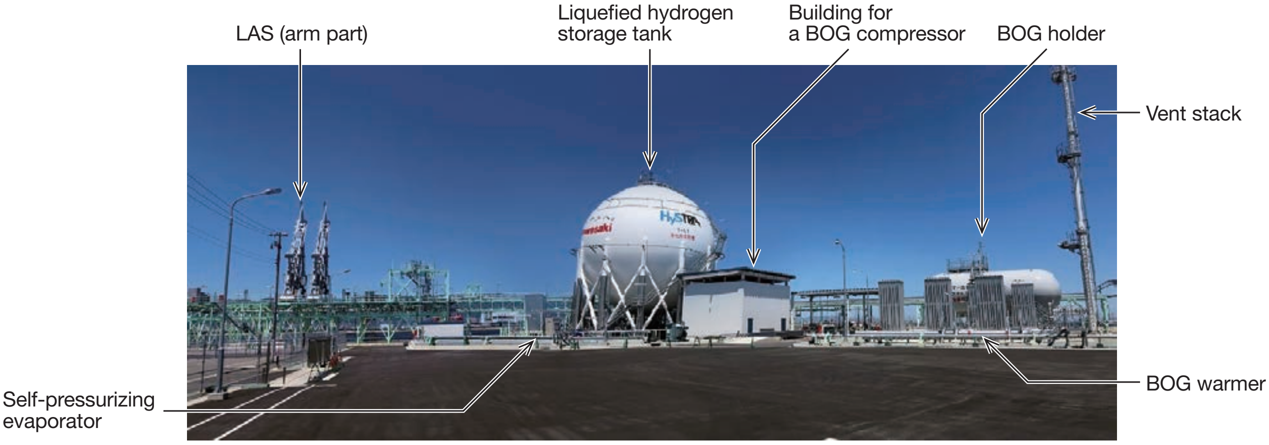


Fig. 9 Liquefied hydrogen unloading terminal on the Kobe Airport Island

Fig. 10 Cogeneration facility with flexibility in the fuel mixing ratio of hydrogen to natural gas

Kawasaki's demonstration on April 19 and 20, 2018 was a complete success. The cogeneration system can change the fuel mixture ratio of hydrogen and natural gas within five minutes while it is running, and has the same properties, including generating-end efficiency, as the same system Kawasaki manufactures for natural gas applications.

5 Toward commercial operation

Japan-Australia pilot demonstration projects are approximately 1/120 of commercial scale by capacity of the liquefied hydrogen carrier. Therefore, after the pilot project, we must incorporate the outcomes and scale up various technologies, equipment, and systems toward commercial operation.

Since July 2019, Kawasaki has been working on scaling-up development of equipment and systems for a liquefied hydrogen energy supply chain toward commercialization in cooperation with Tokyo Boeki Engineering Ltd., Ebara Corporation, IHI Rotating Machinery Engineering Co., Ltd., and others, and we aim to complete such technology development by the end of fiscal 2022.

Conclusion

As hydrogen energy contributes not only to decarbonization but to energy security, economy, and job creation, many countries are launching demonstration projects. In step with Japan's policies leading the movement, Kawasaki has been striving to develop and demonstrate the technologies ahead of others, and is steadily making progress. As our next step, we would like to make use of our efforts to conduct businesses that realize a hydrogen economy, which some are saying will arrive earlier than expected.

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We would like to express our deep gratitude to stakeholders for offering their great cooperation with our projects, and to supervisory authorities and local governments for subsidizing and supporting our projects and establishing relevant rules.

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Hydrogen Production
– Development of Hydrogen Production Technologies

To realize a hydrogen energy supply chain, hydrogen production technologies, which are needed at the initial stage of the supply chain, should be established. There are several methods for producing hydrogen, but as a method for producing a large amount of inexpensive hydrogen, we have focused on hydrogen production from brown-coal, which is an unutilized resource, and renewable energy. We are now working on developing and establishing the technologies necessary for these hydrogen production methods.

Introduction

The main issue in the hydrogen production phase, the initial stage of a hydrogen energy supply chain, is how inexpensively we can produce a large amount of hydrogen, but they must be CO_2-free hydrogen production technologies.

1 Background

The current major methods of hydrogen production in industry are by-product hydrogen from petrochemical plants and steelworks, and natural gas reforming. There are some facilities producing hydrogen through biomass gas reforming, but not on a big scale.

By-product hydrogen may require additional facilities to increase its purity because some impurities can get mixed in depending on the production process. Above all, the amount of production depends on the amount produced of the original product and thus by-product hydrogen is not suitable for stable mass production. Since natural gas reforming is affected by the amount produced and cost of natural gas, which is a primary source, from the viewpoint of energy security as diversification of the energy source, it would be better to produce hydrogen from other raw materials and energy resources.

Brown-coal is not being effectively used as an energy resource even though there is so much reserves of it all over the world, especially Australia. That is why Kawasaki focused on the use of brown-coal as a method of hydrogen production and has worked on establishing technologies that use it to produce a large amount of inexpensive hydrogen. With the increasing utilization of renewable energy in recent years such as wind power and photovoltaics, the price of CO_2-free electricity will become lower in the future. For this reason, we have also worked on establishing technologies that produce hydrogen by water electrolysis using such electricity.

2 Development overview

Brown-coal is an early stage coal with high water content, which makes worse transport efficiency, and it can easily cause self-ignition when it dries. It has thus only been used for power generation near mining sites, but Kawasaki is focusing on potential in brown-coal and has worked on developing hydrogen production technologies to utilize it further. As shown in **Fig. 1**, one method is to burn brown-coal in a gasifier and then only extract the hydrogen gas from the generated gases. We have tried to develop the gasification technology and the gas refining technology to extract high purity hydrogen gas, and to verify the technologies at a bench scale test facility built in one of our factories.

In hydrogen production by renewable energy, as shown in **Fig. 2**, hydrogen gas is produced by water electrolysis using electricity generated from wind power and photovoltaics. We have developed unique technologies to enable high efficiency hydrogen production, and along with this, we have conducted demonstration tests to verify the technologies attaching a small-scale prototype electrolyzer to a wind generation facility in Hokkaido.

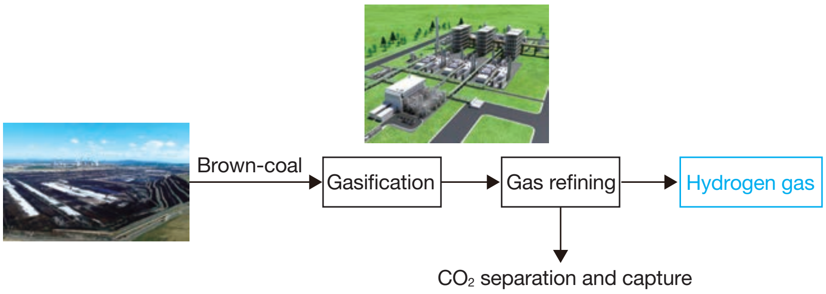

Fig. 1 Process of producing hydrogen from brown-coal

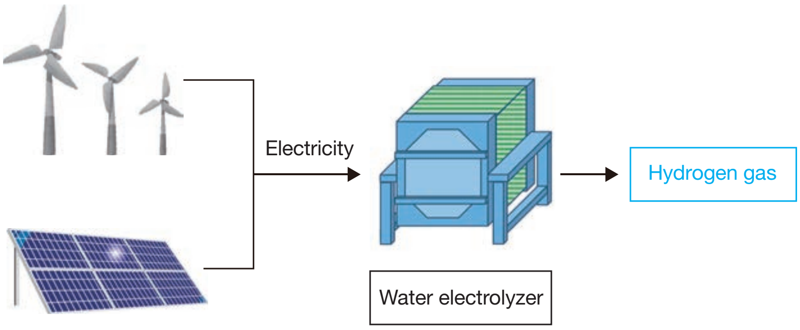

Fig. 2   Process of producing hydrogen by water electrolysis

3 Hydrogen production technology from brown-coal

(1) Hydrogen production by brown-coal gasification

The process of producing hydrogen from brown-coal consists of two major processes, as shown in **Fig. 3**. The first process is gasification to generate syngas consisting primarily of hydrogen, carbon monoxide, and carbon dioxide from raw brown-coal. The second is gas refining to remove carbon dioxide and a small amount of impurities from the syngas and then collect the hydrogen.

(i) Gasification process

In the gasification process, brown-coal pretreatment and gasification are conducted.

① Brown-coal pretreatment

We adopted a wet feed method to supply brown-coal to a pressurized gasifier. In this method, the brown-coal is broken into pieces, mixed with a dispersant and water to convert it into a liquid state called slurry as shown in **Fig. 4**, and the slurry is pumped into the gasifier.

② Gasification

In the gasification process, the brown-coal slurry is pyrolyzed by reaction heat of partial oxidation, which converts it into syngas consisting primarily of hydrogen, carbon monoxide, and carbon dioxide.

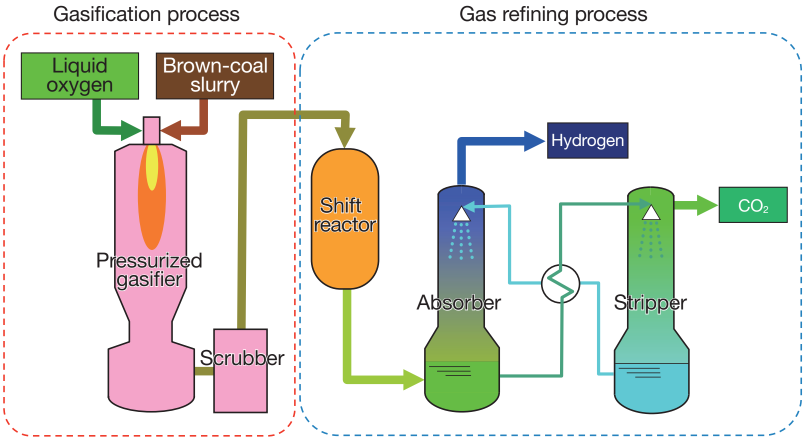

Fig. 3 Process of producing hydrogen by brown-coal gasification

(a) Raw brown-coal (b) Brown-coal slurry

Fig. 4 Raw brown-coal and brown-coal slurry

(ii) Gas refining process

In the gas refining process, the shift reaction and CO_2 separation and capture are conducted.

① Shift reaction

In the shift reaction process, carbon monoxide, which makes up approximately 10 to 20% of the syngas, is reacted with water vapor via a catalyst to produce hydrogen and carbon dioxide, which improves the yield of hydrogen. There are two kinds of shift reaction: the sour shift reaction that requires sulfur, and the sweet shift reaction that does not.

② CO_2 separation and capture

The method of CO_2 separation and capture is selected according to the type, pressure, amount, and purity of the target gas which could be combustion emission gas or gasification gas, for example. Major methods include chemical absorption, in which CO_2 reacts with a liquid absorbent; physical absorption, in which CO_2 is dissolved in a liquid absorbent under high pressure and low temperature; adsorption, in which CO_2 is adsorbed by activated carbon or zeolite; and membrane separation in which CO_2 is separated out with a polymer membrane.

(2) Technology development

(i) Gasification process

① Brown-coal pretreatment

Although brown-coal has high water content at around 60%, we set a target of having at least 53% brown-coal in the slurry (i.e., 47% or less water content) from the standpoint of economic feasibility. In order to decrease the water content in the powdery brown-coal when mined and make the brown-coal into a highly concentrated, less viscous liquid, the surface structure had to be changed to prevent dried brown-coal from reabsorbing moisture, which is known as reforming treatment. In this project, we developed brown-coal pretreatment technologies that can dry and perform the reforming treatment on the brown-coal at the same time, which gave us a reason to adopt the wet feed method.

② Gasification

We developed a gasifier ourselves to understand the brown-coal gasification characteristic and optimize the downstream gas refining process. This gasifier has its slurry burner installed at the top where it gasifies brown-coal slurry, its wall has a fireproof heat-insulation structure, and at the bottom it has a function to directly cool the syngas. The gasifier can conduct oxygen-blown gasification in a 0.4 MPa pressurized environment, and each part is sealed with gas (CO_2) to raise the hydrogen content.

(ii) Gas Refining Process

① Shift Reaction

As brown-coal contains sulfur, the syngas generated by gasification contains sulfuric gases such as hydrogen sulfide as impurities. We thus adopted the sour shift reaction method, which does not require the removal of the sulfur content, can utilize sulfur as a catalytic activator, and is an easier system to operate.

② CO_2 separation and capture

For commercial use, the physical absorption method, which uses the pressure of a gasifier's highly pressurized gas, has a stronger track record, but because the syngas pressure supplied from the gasifier was not high enough at 0.3 MPa in our bench scale test, we adopted the chemical absorption method. Also, as a new technology, we developed a new adsorption method that uses an adsorbent with a liquid chemical absorbent supported on carrier. This method enables us to separate and capture CO_2 at a lower temperature than with the normal chemical absorption method.

(3) Technology verification through a bench scale test

As shown in **Fig. 5**, we attached a gas refining facility to a pressurized gasifier in our Akashi Works, and conducted a demonstration test for bench-scale hydrogen production from September 2012 to February 2013.

Fig. 5 Overall view of bench scale test facility

(i) Test objectives

Shift reaction equipment and CO_2 separation and capture equipment need to be combined in multiple stages to make a complete process that can be successfully established for business purposes. In our bench scale test, we tested hydrogen production from brown-coal by verifying each piece of equipment to meet capacity requirements in a single step.

(ii) Test results

Figure 6 shows the results of the test where we refined syngas generated from brown-coal in the pressurized gasifier with the shift reaction method and chemical absorption method. The amount of gas at the shift reactor outlet increased because water vapor was added, and the amount of gas at the absorber outlet decreased because CO_2 was removed. The test results were that approximately 83% of the carbon monoxide was converted in the shift reactor; almost 100% of the carbon dioxide was captured in the absorber; and a hydrogen concentration of approximately 86% was achieved. Each item met the designed value.

In addition, when we refined the gas with the shift reaction and adsorption methods we developed as new technologies, the hydrogen concentration at the adsorption outlet was over 80% and both methods met the designed value. In this way, we have successfully verified that hydrogen can be produced from brown-coal.

4 Hydrogen production technology by water electrolysis

(1) Hydrogen production by alkaline water electrolysis

Hydrogen production methods by water electrolysis can be classified into three major types: alkaline water

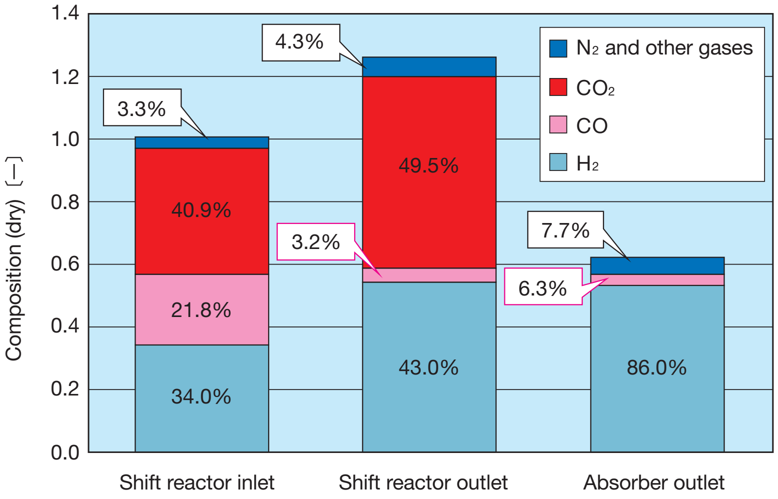

Fig. 6 Results of bench scale test — chemical absorption method

electrolysis, proton exchange membrane electrolysis, and solid oxide electrolysis [1]. The first two have reached the stage of practical use. We chose to focus our development on the alkaline water electrolysis method, which has more advantages in terms of future scalability and cost effectiveness.

Alkaline water electrolysis uses the electrolysis cell shown in **Fig. 7**, which consists of an electrolyte of potassium hydroxide solution, electrodes (an anode and a cathode), and a diaphragm. When electricity passes between the electrodes, hydrogen gas is generated at the cathode, and oxygen gas is generated at the anode.

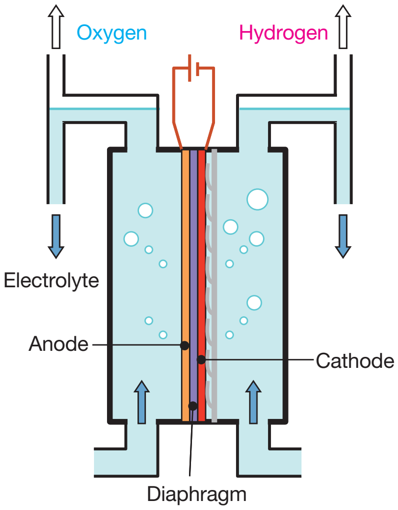

Fig. 7 Schematic diagram of alkaline water electrolysis cell

(2) Technology development

Some of the technical challenges facing alkaline water electrolysis are ensuring a high level of safety and improving electrolysis efficiency. In particular, there is a phenomenon called crossover in which a small amount of oxygen gas gets in the hydrogen gas lines. The major challenge to improving safety and ensuring that high purity hydrogen gas is produced is reducing crossover as much as possible.

As electrodes greatly contribute to electrolysis efficiency, the key is to improve the catalytic activity reaction of the anodes, which generate oxygen. To increase the activation of an anode while maintaining its durability, Kawasaki has collaborated with an electrode manufacturer and a university laboratory to conduct research on topics such as optimization of a catalyzer's constituent elements and layer structure in hopes of achieving high durability and high performance.

In addition, we have researched and developed a diaphragm within our organization. While a diaphragm's gas separation ability contributes to suppressing crossover by hydrogen gas, at the same time, ion permeability is also required to improve electrolysis efficiency, and these two are in a mutually conflicting relationship. So, we optimized its constituent materials, thickness, and layer structure, and successfully developed a high-performance diaphragm that can ensure excellent performances both in ion permeability and in gas separation.

(3) Demonstration project in Hokkaido

Kawasaki conducted a demonstration operation of an alkaline water electrolyzer installed with the technologies mentioned above under a project known as, "Research and

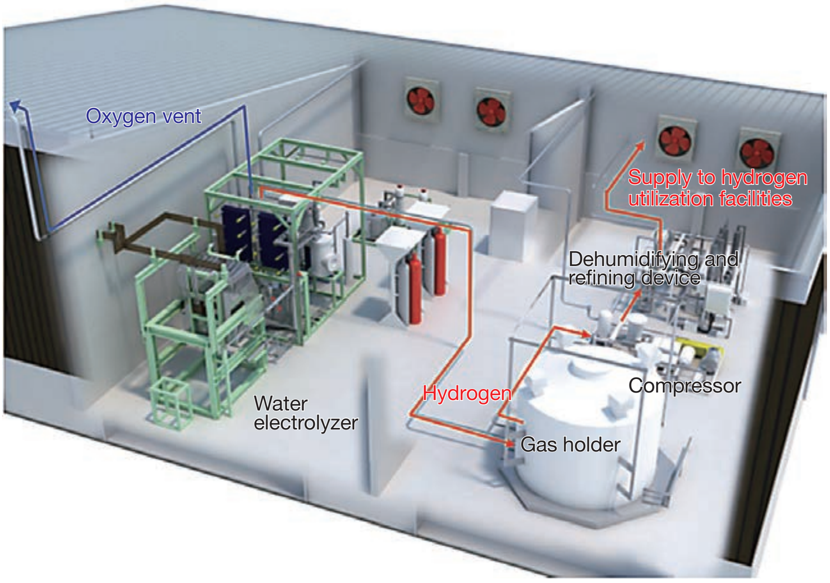

Fig. 8 Schematic image of demonstration plant (only within the scope of Kawasaki Heavy Industries, Ltd.)

Development on Stabilization, Storage and Utilization of Unstable Renewable Electricity In Hokkaido Using Hydrogen-Based Technologies," commissioned by the New Energy and Industrial Technology Development Organization (NEDO)2). In this project we attached a water electrolyzer to wind power generation facilities (a renewable energy), produced hydrogen by using part of the electricity generated there, and then demonstrated a system supplying the optimum quantity of electricity and hydrogen on demand.

Our main scope was hydrogen production using the alkaline water electrolyzer, in this system hydrogen gas produced by the electrolyzer was pressurized to 0.9 MPaG with a compressor, refined the compressed gas with a dehumidifying and refining device, and then supplied the gas to hydrogen utilization facilities (scope of one of co-implementers), as shown in **Fig. 8.**

The result of our demonstration, under the severe operating condition, which was a current density of 6.4 kA/m^2, was that electricity was provided into the alkaline water electrolyzer, but it achieved very high electrolysis efficiency (in high calorific value) exceeding 84% at best. We also obtained excellent results on the purity of the hydrogen gas produced in that the hydrogen gas contained less than 0.1 vol% oxygen (in dry base), verifying the high gas-separation ability of the diaphragm we developed.

Water electrolysis technologies are becoming more important for further promotion of renewable energy and establishment of a hydrogen-based society in the future. Kawasaki will continue to work on further improvement of durability and further cost reduction for key components such as electrodes and diaphragms, as well as studies on future commercialization.

Conclusion

Kawasaki believes that, through such technology development, we came to recognize what technologies were required to produce a large amount of inexpensive hydrogen and established the fundamental technologies for building a hydrogen energy supply chain in the future.

For the hydrogen production technologies by water electrolysis in the project in Hokkaido, we received tremendous support from NEDO, who commissioned the project, and co-implementers including Toyota Tsusho Corporation. We would like to sincerely thank everyone for their help.

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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

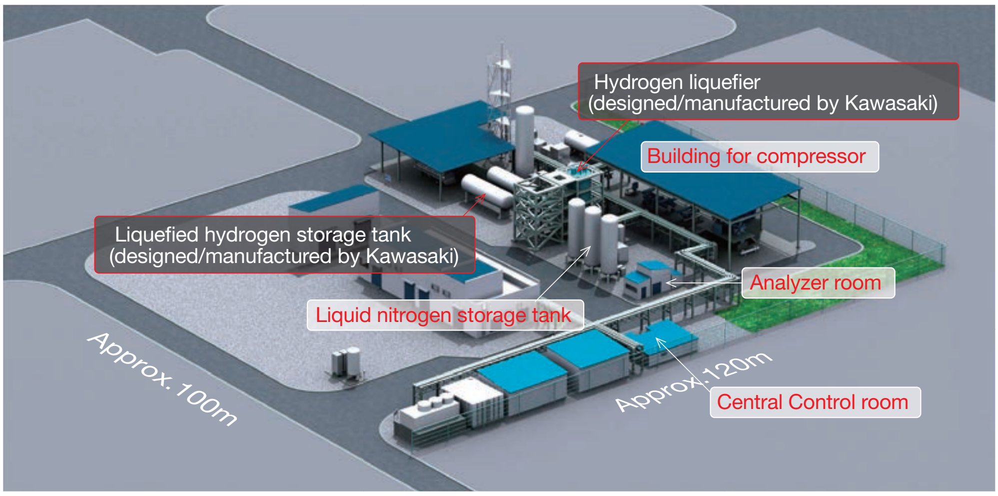

Fig. 1 Schematic diagram of hydrogen liquefaction system (demonstration facility in Harima Works)

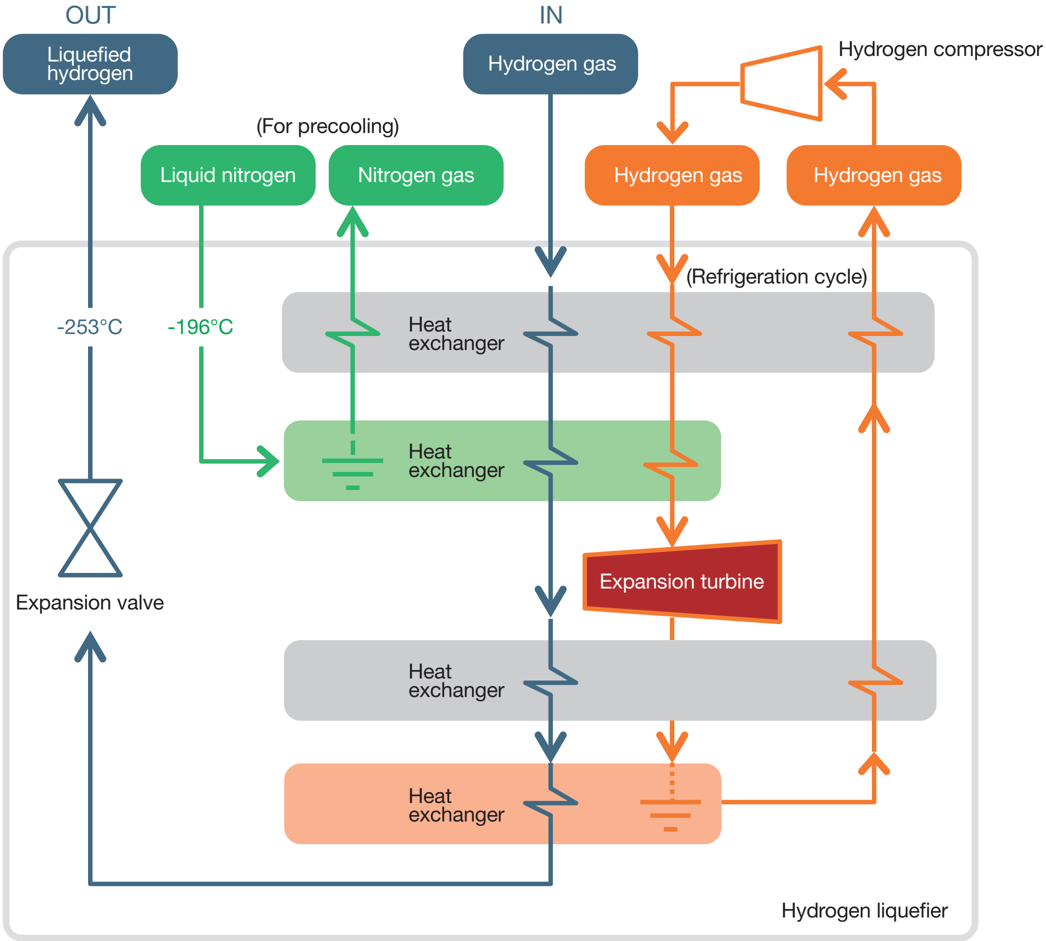

Fig. 2 Schematic process flow diagram of hydrogen liquefaction system

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

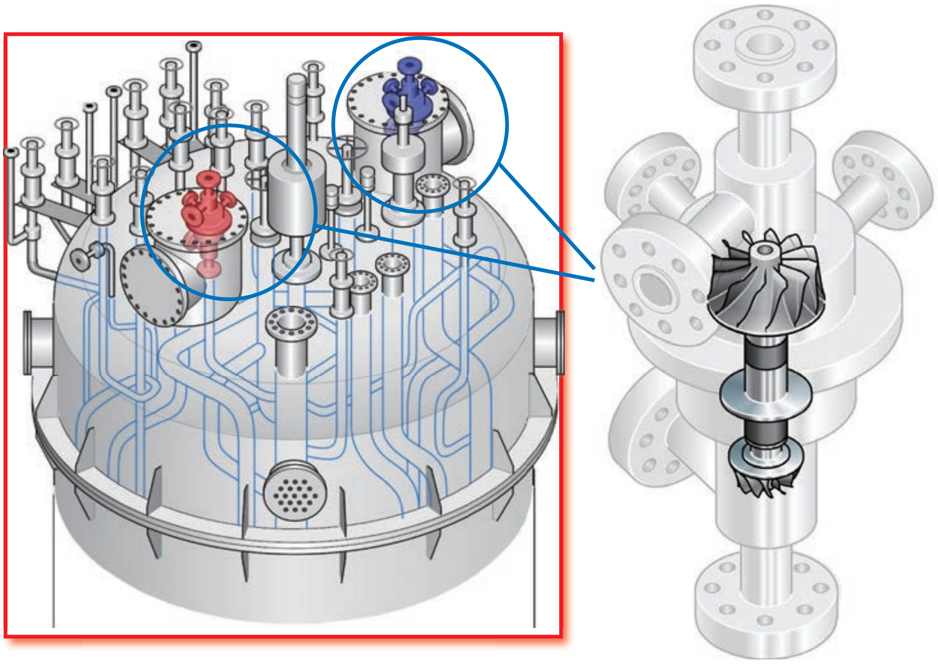

Fig. 3 Hydrogen liquefier (upper part) and expansion turbine

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

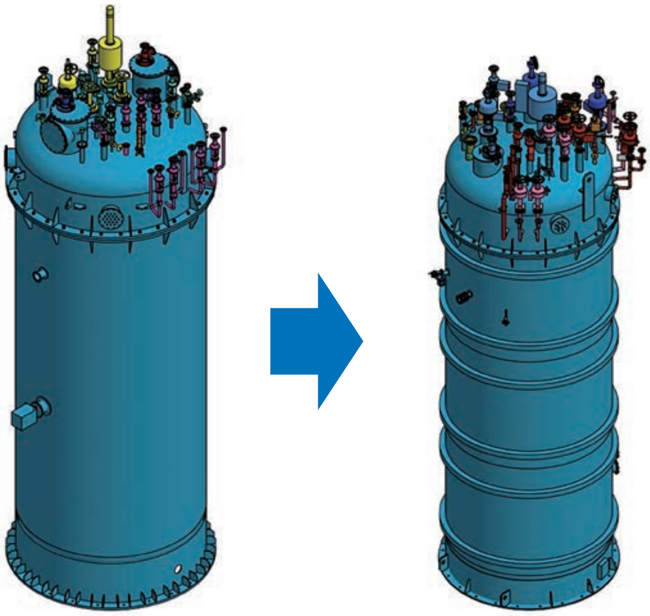

Fig. 4 Prototype liquefier (left) and new liquefier (right)

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.

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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


Source：HySTRA

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

Photographed in May 2020

Fig. 3 Liquefied hydrogen storage tank

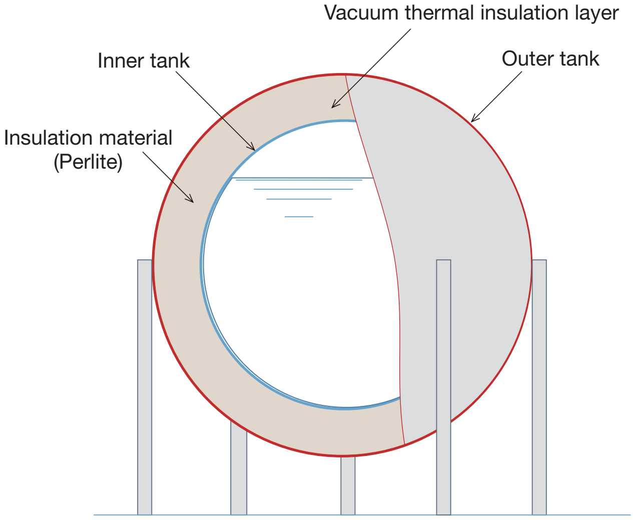

Fig. 4 Conceptual diagram of vacuum thermal insulation structure

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

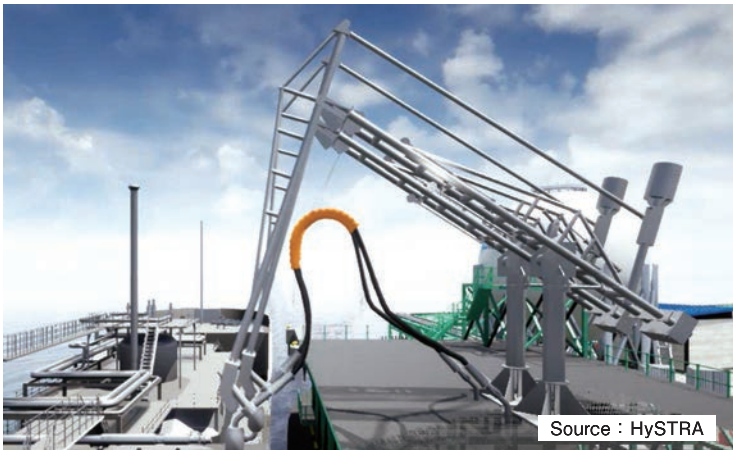
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Fig. 5 Image of a ship connecting to terminal

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

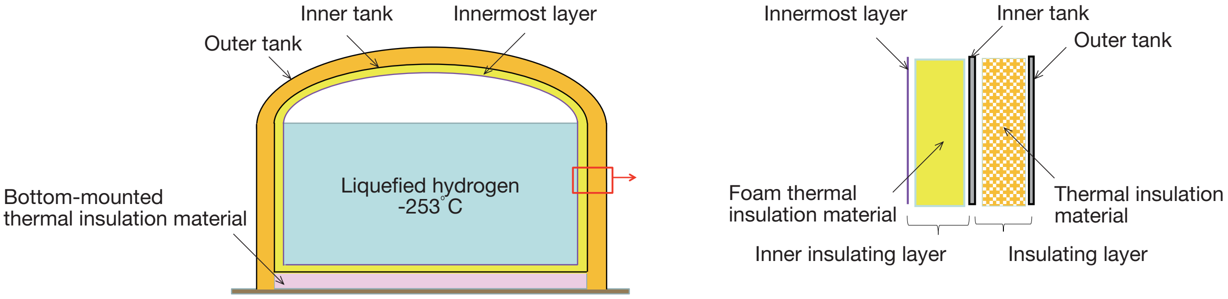

Fig. 7 Structural design of a large-scale tank

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.

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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

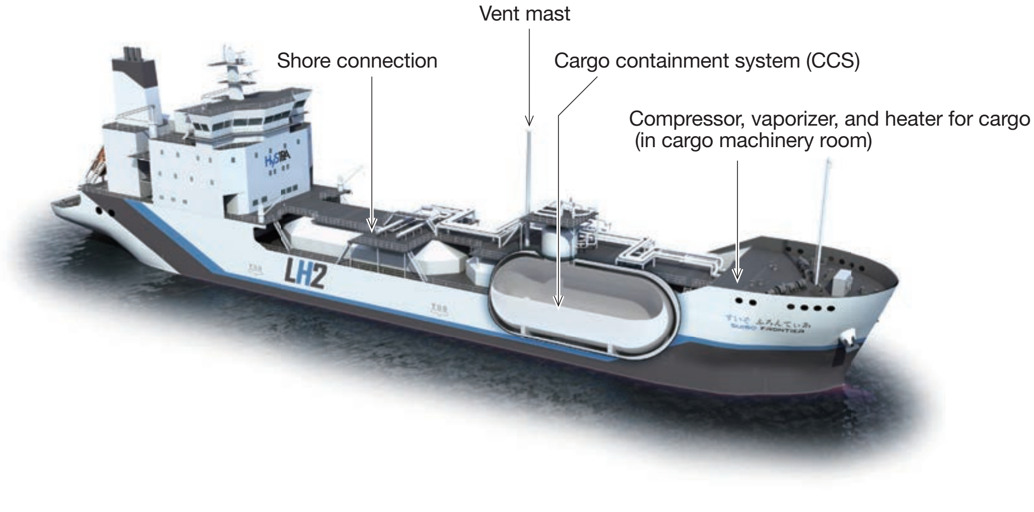

Fig. 1 Pilot demonstration carrier

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

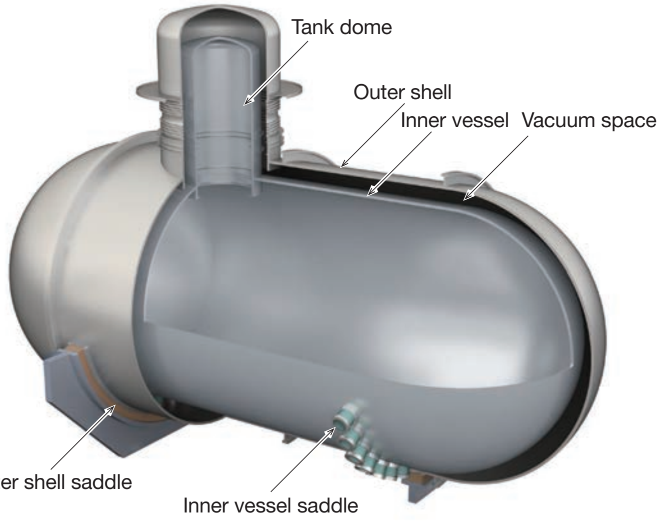

Fig. 2 CCS's double-shell structure

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

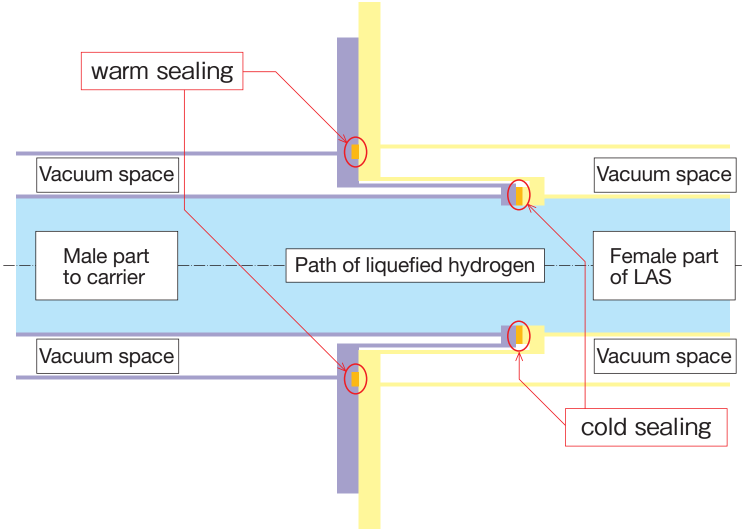

Fig. 3 Bayonet joint

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.

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Hydrogen Utilization – Development of Hydrogen Fueled Power Generation Technologies

Hydrogen is used as fuel for transport machinery such as rockets and FCV (fuel cell vehicles/buses).

To realize low carbonization and a future hydrogen-based society, Kawasaki is developing hydrogen combustion technology and power generation technologies for gas turbine engine, which is excellent in fuel flexibility. In 2018, we successfully operated the world's first hydrogen fueled power generation in an urban area, and we have been improving such technologies to achieve higher performance and cleaner power generation.

Introduction

To realize a hydrogen energy supply chain, it is important to lower the price of hydrogen to around the current price of fossil fuels such as oil and natural gas. The demand and consumption of large amounts of hydrogen will lead to a hydrogen cost reduction though economies of scale.

1 Background

Hydrogen has long been used as fuel for rocket propulsion and FCVs (fuel cell vehicles/buses), as well as for gas turbine power generators and boilers. According to Japan's Strategic Roadmap for Hydrogen and Fuel Cells, hydrogen fueled power generation will enter the mainstream around 2030. If hydrogen can be utilized as fuel for power generation in place of natural gas, that will lead to mass hydrogen utilization and contribute greatly to the realization of a hydrogen energy supply chain.

In preparation for the spread of hydrogen utilization, every gas turbine manufacturer is working on projects to make use of the excellent fuel flexibility of gas turbine engines, for instance, projects to develop combustion technology that can run on either a mix of hydrogen and natural gas or 100% hydrogen, and to realize practical application of gas turbine power generation systems.

Kawasaki is currently developing clean hydrogen combustion technology and in the process of verifying that technology for hydrogen fueled power generation, with the aim of achieving hydrogen fueled power generation using small- and medium-sized gas turbine power generation systems.

2 Challenges facing hydrogen utilization in gas turbines

Figure 1 shows the structure of a small gas turbine. Fuel is injected into the combustor where it is ignited in air pressurized by a compressor to generate high-temperature pressurized combustion gas. The flow of this combustion gas rotates a turbine, allowing power output to be obtained. The combustor's role is to stably and cleanly generate combustion gas whose temperature exceeds the melting point of metals.

Many different kinds of fuel can be used with gas turbines, including hydrogen, but it requires combustion technology adapted to hydrogen's unique combustion properties. The key to realizing hydrogen fueled power generation is to develop combustion technology and combustor parts that can achieve both stable hydrogen combustion and low emission of nitrogen oxides (NOx), an air pollutant [1).

(1) Stable hydrogen combustion

Hydrogen has higher reactivity than natural gas and the flames of its combustion come very close to combustor parts, which is more likely to cause the temperature of the parts to rise and combustion instability. **Figure 2** shows the state of flames inside of a combustor in combustion tests

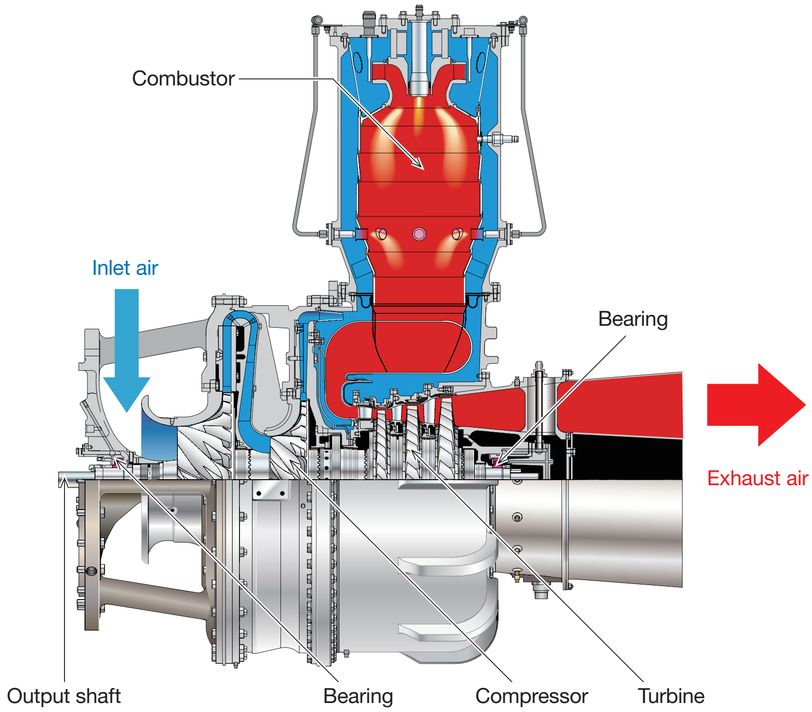
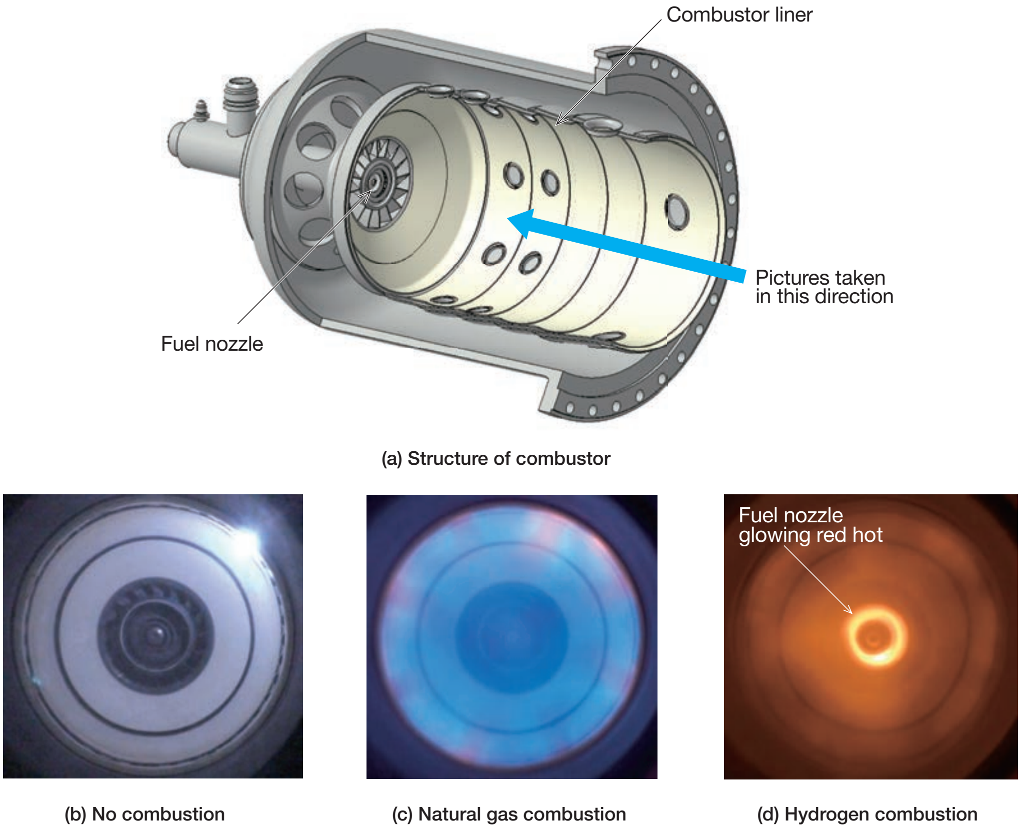


Fig. 1 Small-scale gas turbine (M1A-17D)



(a) Structure of combustor

(b) No combustion

(c) Natural gas combustion

(d) Hydrogen combustion

Fig. 2 Combustor structure and combustion state

using natural gas and hydrogen with a fuel nozzle for natural gas. In the hydrogen combustion test, hydrogen flames and combustion gas got too close to the fuel nozzle parts, making them so hot they glowed red.

Because there is a high-speed turbine rotation in the stage after the combustor, if the combustor is damaged in any way, such as a part falling off and entering the next stage, the turbine may be broken and the engine will stop. For this reason, it is important to take measures such as giving combustor parts shapes that make it possible to maintain stable combustion even with hydrogen.

(2) Reduction of nitrogen oxides

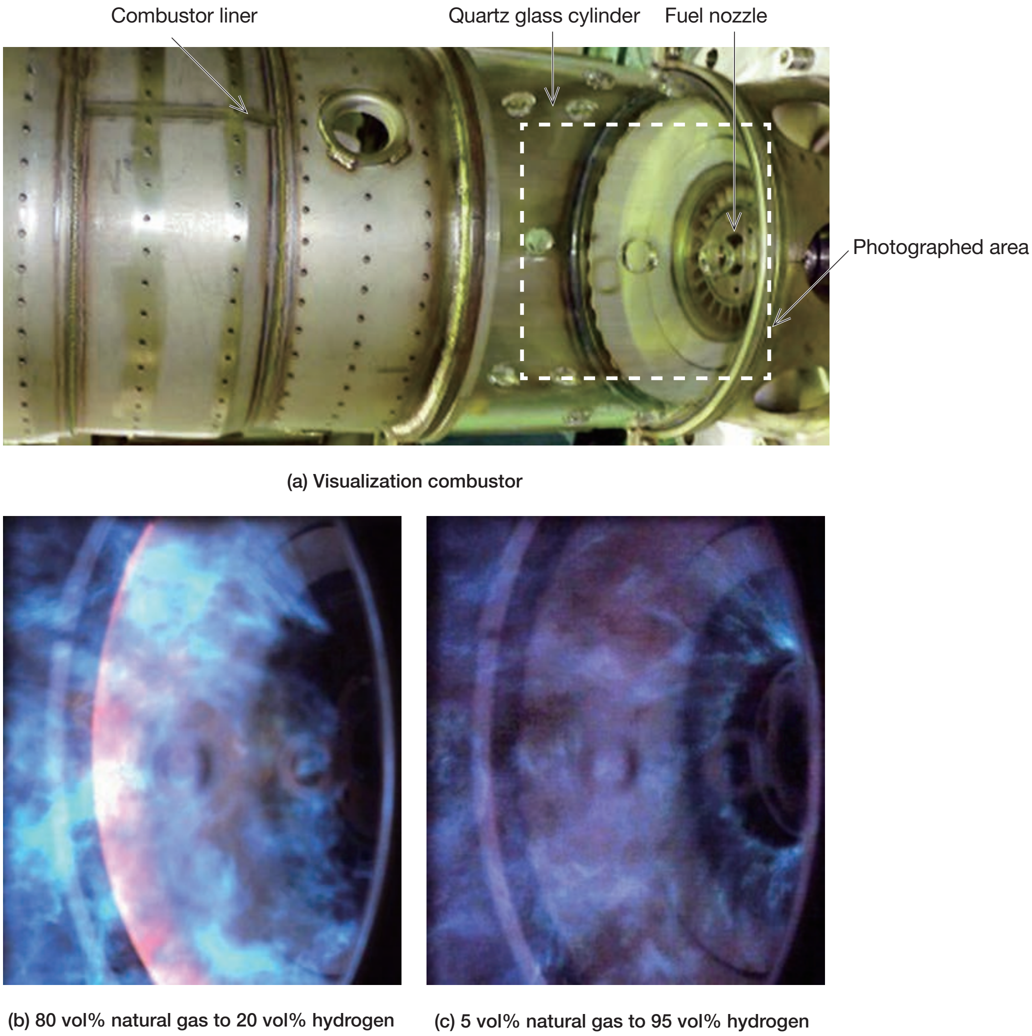
Figure 3 shows images of a visualization combustor in which part of the combustor was replaced with a quartz glass cylinder to make it possible to research the flames generated by igniting a hydrogen/natural gas mixture in the combustor; and the appearance of the flames taken with a high speed camera. When the proportion of natural gas was larger, as shown in **Fig. 3** (b), the flames were formed farther away from the fuel nozzle. On the other hand, when the proportion of hydrogen was larger, as shown in **Fig. 3** (c), the flames were formed closer to the fuel nozzle. Due to this difference in reaction areas and the rise in local flame temperature, when hydrogen is combusted in a gas turbine combustor, nearly 2 to 2.5 times more NOx is produced than with natural gas. Reducing the amount of NOx produced is also a major issue.

3 Development progress on hydrogen fueled gas turbines

There are mainly two types of combustion technologies for NOx reduction in gas turbine. One is diffusion flame combination with water injection that reduces NOx by spraying water or steam into a combustor, which has high combustion stability, and the other is dry low emission that reduces NOx by other methods such as adjusting the way air and fuel are mixed together.

In the case of diffusion flame combustion in which fuel gas is injected into the air and ignited, all that is required in order to accommodate hydrogen combustion is to take measures for the temperature rise of combustor parts. Kawasaki adopted water injection to establish technologies for the entire hydrogen fueled gas turbine power generation system.

However, with water injection, pure water production equipment must be installed to supply water and steam



(a) Visualization combustor

(b) 80 vol% natural gas to 20 vol% hydrogen

(c) 5 vol% natural gas to 95 vol% hydrogen

Fig. 3 Visualization combustor and flame behavior and so running costs will rise. That is why we are also implementing research and development on a new dry low emission combustor suited to hydrogen combustion.

(1) Technology demonstration for hydrogen fueled gas turbine power generation

In a grant project by the New Energy and Industrial Technology Development Organization (NEDO), called the Smart Community Technology Development Project Utilizing Hydrogen Cogeneration Systems, Kawasaki worked on a hydrogen cogeneration system with a focus on the development of hydrogen-fueled and natural gas and hydrogen mixture-fueled gas turbines[1], [2].

In this project we employed a 1MW-class PUC17D Generator for Ordinary Use, which is equipped with our M1A-17D Gas Turbine Engine, which has a hydrogen combustion-compatible combustor. This generator has high fuel flexibility to allow for operation with 100% hydrogen fuel, natural gas, and natural gas/hydrogen blends mixed at any desired ratio.

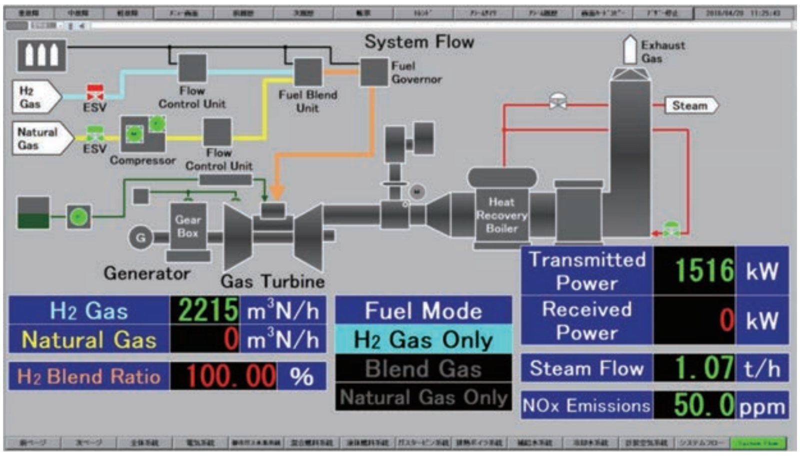
Figure 4 is an overall view of our hydrogen gas turbine cogeneration system demonstration plant installed on Port Island in Kobe City. After completion of the plant in December 2017, we carried out trial operation of the gas turbine power generation system alone and operation tests using natural gas, and then conducted demonstration tests to supply both heat and power with a natural gas/hydrogen blend and 100% hydrogen.

In a demonstration test held on April 19 and 20, 2018, this system was fueled with 100% hydrogen at a rate of approximately 2,200 Nm^3/h, and it successfully supplied 2,800 kW of heat (steam) to two neighboring facilities and 1,100 kW of electricity to four neighboring facilities at the same time, which is the world's first successful example of cogeneration using hydrogen fueled gas turbine power generation in an urban area. **Figure 5** is a picture of a monitor for the operation monitoring system during this demonstration test. We achieved NOx 50 ppm (O_2-16%) by

(a) Exterior of facility

(b) PUC17 Generator for Ordinary Use

Fig. 4 Hydrogen gas turbine cogeneration system demonstration plant



H2 Gas 2215 m^{3}N/h

Natural Gas 0 m^{3}N/h

H2 Blend Ratio 100.00 %

Fuel Mode

H2 Gas Only

Blend Gas

Natural Gas Only

Transmitted Power 1516 kW

Received Power 0 kW

Steam Flow 1.07 t/h

NOx Emissions 50.0 ppm

Fig. 5 Operation monitoring system (when operating on 100% hydrogen gas) water injection, which met the threshold of 70 ppm (O_2-16%) set by Japan's Air Pollution Control Act.

(2) Development of hydrogen dry low NOx combustion technology

Natural gas achieves dry low NOx combustion by lean premixed combustion, in which the air and natural gas are mixed in advance and then the mixed gas is combusted. On the other hand, as hydrogen has high reactivity and causes combustion instability like flash-back, it is very difficult to use dry low NOx combustion with it.

For this reason, Kawasaki has studied the application of micro-mix hydrogen combustion technology to industrial gas turbines. This is a hydrogen dry low NOx combustion technology that uses small hydrogen flames. As shown in **Fig. 6**, hydrogen injected from small hydrogen injection holes less than a millimeter in diameter is rapidly mixed with a cross jet flow of air, which forms small hydrogen

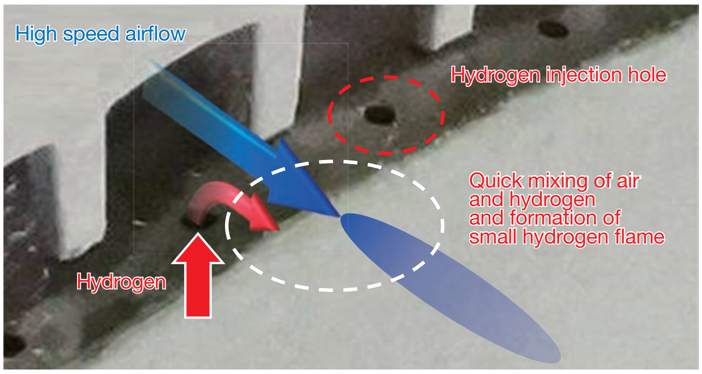


Fig. 6 Micro-mix hydrogen combustion technology

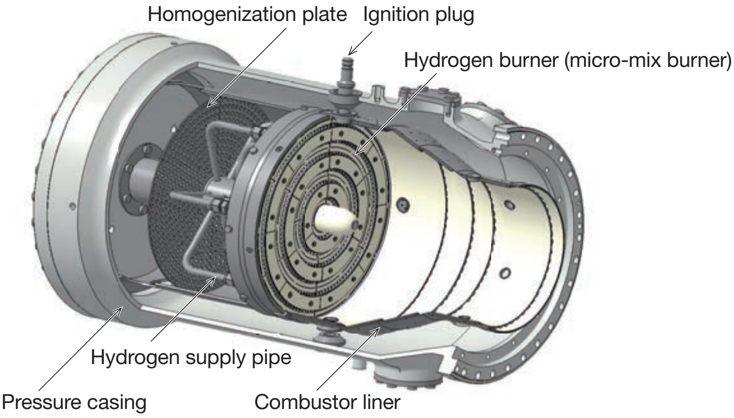
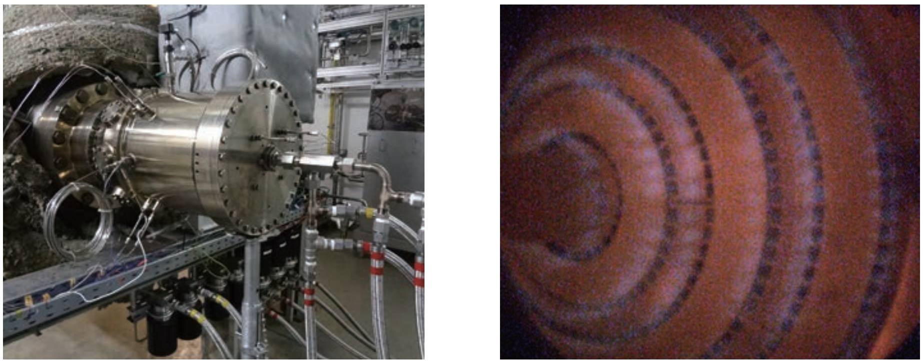


Fig. 7 Hydrogen dry low NOx combustor for 2MW class gas turbine



(a) Trial combustor

(b) Inside of combustor in design condition equivalent

Fig. 8 Tests of hydrogen combustor

flames with high flame stability, and also reduces NOx by shortening the reaction time.

Figure 7 is a hydrogen dry low NOx combustor for a 2MW class gas turbine. The hydrogen burner is in the shape of a ring, and the number of rings can be changed according to the hydrogen flow rate (operation conditions) 3), 4). This enables both high combustion efficiency from the time the engine starts to lower load operation conditions and low NOx combustion during higher load operation conditions.

We used trial combustor test parts to obtain ignition and flame stability performance, and combustion characteristics, NOx emissions in design conditions. **Figure 8** (a) shows a trial combustor installed in a facility that can replicate high temperature and high pressure combustor inlet boundary conditions that are the same as a 2MW class gas turbine, and **Fig. 8** (b) shows the hydrogen flame behavior inside the combustor under conditions equivalent to 100% of the design load.

In this test we confirmed stable hydrogen combustion and achieved less than NOx 35 ppm (O_2-16%), which is half of the regulation value, in the range of 50% load to 100% design load operation equivalent.

In May 2020, we started demonstration operation of the gas turbine engine installed in this combustor in the hydrogen gas turbine cogeneration system demonstration plant shown in **Fig. 4**, and successfully generated power using hydrogen dry low NOx power generation for the first time in the world.

Our next step has been proceeding with performance verifications such as stable operation and power generation efficiency, and to reduce the environmental load.

Conclusion

As part of the realization of a hydrogen energy supply chain, Kawasaki is developing technology for hydrogen combustion and a hydrogen fueled gas turbine. We believe such technologies will make it possible to use hydrogen as fuel for gas turbines, like natural gas, and can greatly contribute to the realization of a low-carbon society and a hydrogen-based society in the future.

The contents in this chapter include the results achieved with NEDO's support, namely, two grant projects, the Demonstration Project for Establishment of Mass Hydrogen Marine Transportation Supply Chain Derived from Unused Brown Coal, and the Smart Community Technology Development Project Utilizing Hydrogen Cogeneration Systems, and the commissioned project, Research and Developments of Hydrogen Combustion Technology for Hydrogen Gas Turbines. We would like to express our deep gratitude to NEDO.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Product Safety Assessment Initiatives for a Hydrogen Society

In our hydrogen energy supply chain pilot project, for safer use of hydrogen products, we had many phenomenological experiments, numerical analysis and risk assessments to clarify the hydrogen behavior. And we are also developing management systems for health, safety, and environment in our project.

Introduction

To establish a hydrogen energy supply chain that supports the realization of a hydrogen-based society, we need to establish a process for evaluating safety that covers the entire life cycle of products in addition to technology development, and also demonstrate to the public that hydrogen products can be used safely.

1 Background

Liquefied natural gas (LNG) is currently used as one of clean energy. In the 1950s, a wide range of technological advancements were made in the transportation, storage, and utilization of LNG, which led to it becoming very widespread throughout society.

The use of hydrogen, on the other hand, started with specialized applications such as rockets, for which Kawasaki developed liquefied hydrogen storage tanks in the 1970s for the Tanegashima Space Center of the Japan Aerospace Exploration Agency (JAXA). Ever since then, more and more hydrogen stations for fuel cell vehicles have opened, and hydrogen is gaining momentum toward full-scale utilization.

To handle hydrogen safely, comprehensive approaches are required, such as phenomenological experiments , numerical analyses and appropriate safety assessments before development and design verification. Moreover, as a product supplier, we need to promote organizational safety efforts through every development phase of the entire product life cycle, from the initial concept to actual use.

2 What is hydrogen?[1)]

(1) Properties of hydrogen

Table 1 shows the physical properties of hydrogen comparing them to methane, the main component of LNG. The liquefied hydrogen improves transport efficiency, but liquefied hydrogen requires more advanced thermal insulation technology than LNG, because its boiling point is approximately 90°C lower and it has smaller latent heat per volume than LNG. Moreover, once vaporized, hydrogen ignites much more easily than methane and burning velocity is faster after ignition, which means it requires prevention measures not only for leakage but also for ignition. Therefore, basic measures are important, such as preventing hydrogen gas leakage, so as not to generate flammable atmosphere within the combustion range, and avoiding ignition sources.

(2) Regulations and guidelines that apply to the hydrogen project

The terminal facilities are built in accordance with the domestic regulations where the construction site is

Table 1 Physical properties of liquefied hydrogen and LNG

Physical property	Hydrogen	LNG (methane)
Boiling point 〔°C〕	−252. 85	−161. 45
Gas density 〔kg/m^3〕	0. 0899	0. 717
Liquid density 〔kg/m^3〕	70. 8	422. 4
Latent heat 〔kJ/L〕	31. 4	246
Flammability limits (in air) 〔vol%〕	4~75	5~15
Minimum ignition energy 〔10^{-5} J〕	1. 6	28

Table 2 Standards and guidelines for hydrogen safety

Scope	Standards and guidelines
Related rules for liquefied hydrogen carriers	Guidelines for Liquefied Hydrogen Carriers, Class NK (2017)
Hydrogen safety	ISO/TR 15916 : Basic considerations for the safety of hydrogen system (2016)
Hydrogen safety	AIAA G-095 : Guide to Safety of Hydrogen and Hydrogen Systems (2014)
Hydrogen facilities	NFPA 2 : Hydrogen Technologies Code (2016)

located. The High Pressure Gas Safety Act is one of them and regulations for hydrogen supply facilities are being developed.

On the other hand, for the carriage of liquefied gases in bulk by ships, the ships should comply with the relevant requirements in the IGC Code, set by the International Maritime Organization (IMO). However, the requirements for liquefied hydrogen are not specified in the Code. For this reason, in 2013 Ministry of Land, Infrastructure, Transport and Tourism established a working group of experts and started discussions on safety standards. Japan made a proposal to the IMO, and interim recommendations for carriage of liquefied hydrogen in bulk were adopted in 2016 2). As the interim recommendations require that safety measures be considered based on a risk assessment, the assessment results on the basic design of the pilot ship Kawasaki designed have been published by the IMO 3). After that, Class NK instituted Guidelines for Liquefied Hydrogen Carriers corresponding to the interim recommendations. Major standards and guidelines are shown in **Table 2**.

3 To Ensure safety

Today, systems are becoming more and more complex at an increasingly fast pace, so it is becoming more difficult to ensure product safety just based on past experience, designing achievements, and complying with the regulations at the time.

In Europe and the U.S. in the energy and chemical plant industry, they not only comply with laws, regulations, and industry standards, but also voluntarily set even stricter standards, and moreover, they have established a product development scheme based on risk assessment by manufacturers or operators. In Japan, related laws and regulations are changing from a specification-based approach that defines specific criteria, to a performance-based approach, which only defines a specific level of performance and leaves it up to manufacturers how they achieve the requirements. In the latter approach, risk assessment becomes an effective method of demonstrating accountability. Risk assessment is a series of steps in which risk inherent in systems is identified, estimated and evaluated. And it determines proper risk reduction measures to be planned according to the results.

In order to provide safety hydrogen products, from a technical standpoint, we are required to design products based on adequate risk assessment results and also to conduct phenomenological experiments to clarify the behavior of hydrogen and numerical analyses using proven methods. Also, from the standpoint of project execution, we are required an integrated approach considering an occupational safety, health, and environmental.

4 Our approaches to safety

One of the most important points for risk assessment is to ensure the completeness of risk identification. As there are several methods of risk assessment, we selected one after considering the features of each method. The major assessment methods we adopted in this pilot project are shown in **Table 3**.

To ensure objectivity, risk assessment was conducted by inviting external experts. Major external safety reviews

Table 3 Risk assessment methods in our pilot project

Method	Features
HAZID（Hazard Identification）	Comprehensively evaluates critical hazards inherent in an object
HAZOP（Hazard and Operability Studies）	Identifies potential hazards in design deviation using a piping and instrumentation diagram (P&ID)
FMEA（Failure Modes and Effects Analysis）	Evaluates equipment failure mode, its effects, and detection methods
Bowtie Analysis	Evaluates cause and consequence, and safety measures, with a focus on possible events

conducted for the pilot project are shown in **Table 4**. An image of a HAZOP study workshop, which is one of the assessment methods, is shown in **Figure 1**.

(1) Hydrogen behavior phenomenological experiment

In order to identify various hydrogen behaviors that can be caused by an accident, we conducted a variety of experiments in collaboration with third parties. **Figure 2** shows the results of liquefied hydrogen and LNG dispersion tests conducted in 2013. In these tests, we released approximately six liters of liquefied hydrogen and LNG from approximately 0.9 meters above stainless steel materials on the ground, observed the consequent vapor cloud distribution, and evaluated the spread speed and the effects caused by the material of the surface onto which the liquids were spilled. It was found that both of the low temperature fluids cooled the surrounding atmosphere and formed vapor clouds during the process of evaporation, but the hydrogen gas showed a higher ascent velocity and smaller horizontal dispersion. In addition, it was observed from the temperature distribution that low temperature gas stagnated on the ground for LNG , but the same behavior was not observed for hydrogen.

(2) Numerical analysis

(i) Hydrogen leak analysis

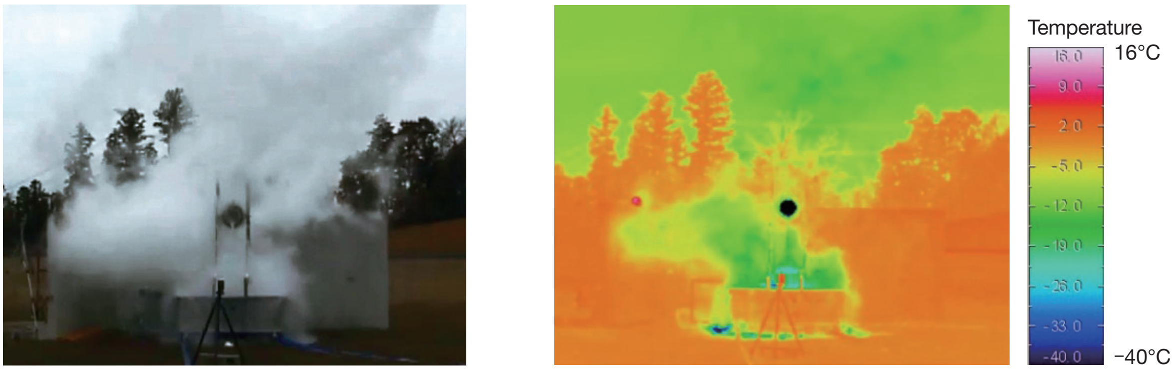
Because a ship has limited space in which to install equipment, some of the hydrogen cargo pipeline and equipment have to be installed in an enclosed space. Under such circumstances, if a hydrogen leakage occurs, it is essential that the leakage be detected immediately and the enclosed space be ventilated to exhaust the leaking gas.

To address that, we first assumed the leakage conditions based on possible scenarios, such as leakage points, cross-section area, direction and physical properties

Table 4 Safety review in our pilot project

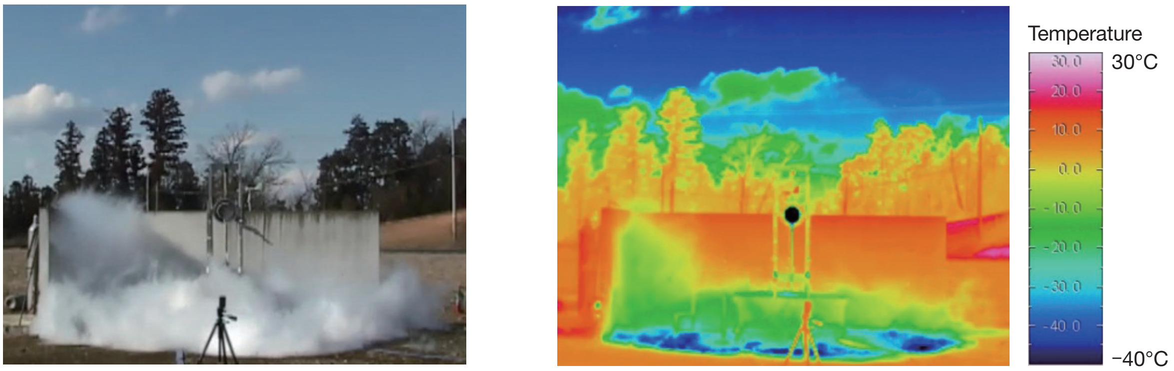
Name	Scope	Conducted in 〔year〕	External expert
Working group on transportation requirement for hazardous liquid bulk cargo	Liquefied hydrogen carrier	2013 to 2019	The University of Tokyo, National Maritime Research Institute, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), etc.
Research Committee of Maritime Disaster Prevention Measures	Kobe loading/unloading terminal and liquefied hydrogen carrier	until 2019	The University of Tokyo, Japan Coast Guard Academy, MLIT, Maritime Disaster Prevention Center, etc.
Committee for the Navigation Safety Measures	Kobe loading/unloading terminal and liquefied hydrogen carrier	2018	Tokyo University of Marine Science and Technology, Kobe University, Ministry of Internal Affairs and Communications, MLIT, Japan Marine Science Inc., etc.

Fig. 1 HAZOP study workshop



(a) Vapor cloud distribution of liquefied hydrogen

(b) Temperature distribution of liquefied hydrogen



(c) Vapor cloud distribution of LNG

(d) Temperature distribution of LNG

Fig. 2 Dispersion tests

and then we performed ventilation analysis for the enclosed space using CFD. Ventilation flow analysis for room-temperature air in a cargo machinery room is shown in **Figure 3**, and hydrogen behavior analysis for when cryogenic hydrogen gas leaks from 5 mm^2 hole is shown in **Figure 4**. In **Figure 3**, each color of the lines represents the air residual time from the inlet port to the exhaust port, which shows that the air taken in from the inlet was ventilated smoothly. **Figure 4** shows that the hydrogen leakage (colored light blue) from a pipe connection quickly reached the exhaust port.

(ii) Analysis of hydrogen behavior in liquefied hydrogen storage tank by rapid pressure release

While we have designed a liquefied hydrogen storage tank adopting state-of-the-art thermal insulation technology, it is impossible to completely prevent the

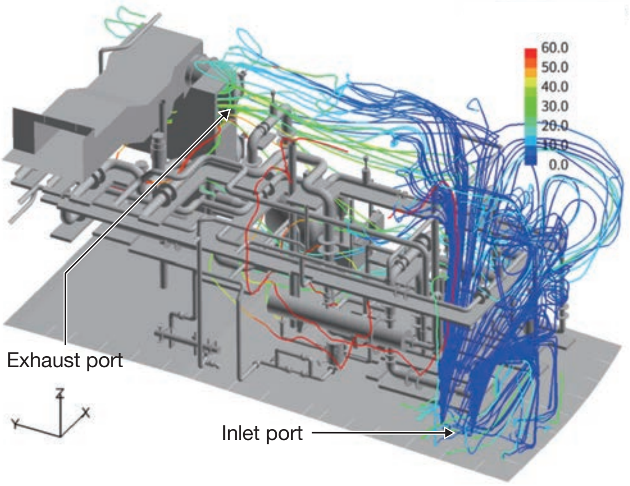


Fig. 3 Ventilation flow analysis for cargo machinery room

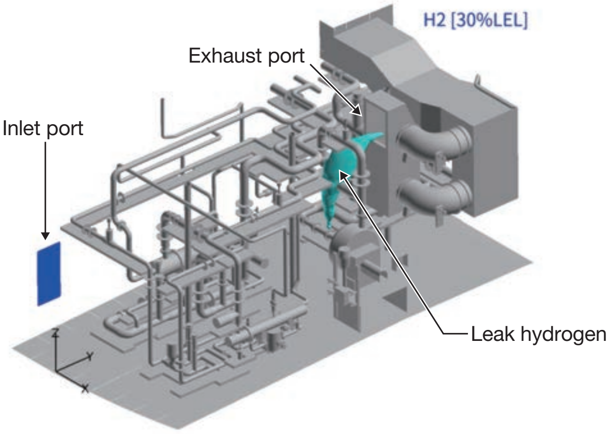


Fig. 4 Hydrogen leakage behavior analysis for cargo machinery room

vaporization of liquefied hydrogen caused by heat ingress into a tank under operation. As hydrogen vaporization by heat ingress increases the pressure inside a tank, we designed our liquefied hydrogen tank at loading/unloading terminals to prevent the internal pressure from exceeding the designated level by releasing boil-off gas from its ventilation facilities. On the other hand, the liquefied hydrogen carrier of this pilot project adopts a pressure accumulator storage tank, which does not release any boil-off gas during the voyage but allows the inner pressure to increase. Because of this, prior to unloading after a voyage, we need to release the internal pressure of the tank to atmospheric pressure. However, when the internal pressure is released too rapidly, the vapor-liquid will lose the thermal equilibrium, which might cause rapid vaporization of liquefied hydrogen.

In order to clarify this complex hydrogen behavior inside a tank, we conducted the rapid internal pressure releasing experiments and numerical analysis for the experiments with the University of Tokyo using the JAXA's 30 m^3

Fig. 5 Liquefied hydrogen storage tank (JAXA)

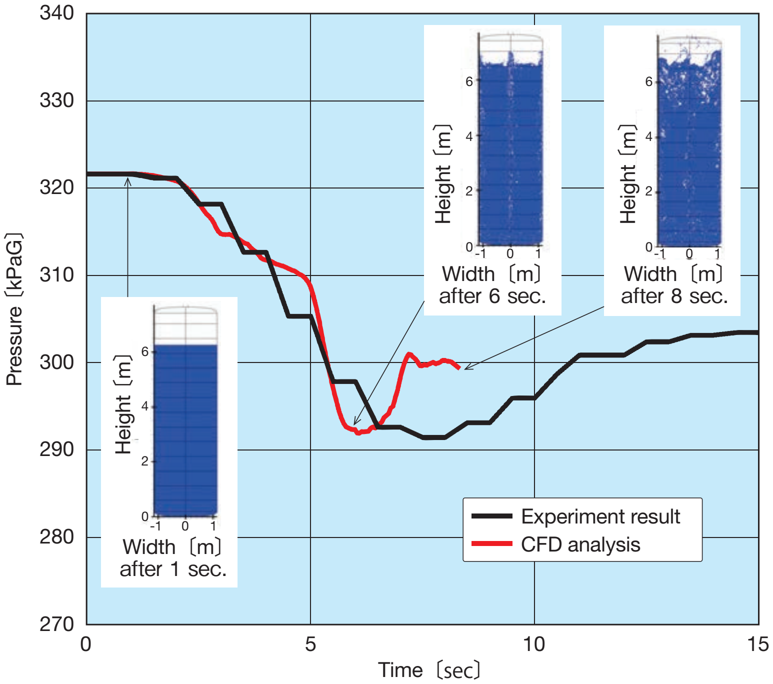


Fig.6 Pressure behavior in the tank after rapid pressure releasing

cylindrical liquefied hydrogen storage tanks, and we are examining the changes in the pressure and temperature inside the tank and analyzing how gas is produced from the liquid phase[4]. **Figure 5** is an image of the storage tank under analysis. **Figure 6** is sample data of the experiments and analysis on the pressure change inside the tank during rapid pressure release. From these results, after a rapid pressure releasing operation, we observed a pressure increasing phenomena, but such pressure change was relatively mild. This phenomena is deeply related to the behavior of a gas phase that is generated in a liquid phase, we are now developing more advanced analysis models as shown in **Figure 6**.

(3) HSE management system

In the overseas energy and chemical plant industory , it is becoming standard for product development to be conducted based on a systematic management system called HSE (Health, Safety and Environment), which is an integrated concepts that includes occupational safety , health and environmental consciousness. HSE requires that risk assessments be conducted voluntarily by manufacturers and they need to establish own management systems to carry out and incorporate such assessments in an effective manner. More and more industries are applying HSE and application of HSE is being a tendering requirement. HSE-based management is becoming the global standard.

CO_2-free Hydrogen Energy Supply-chain Technology Research Association (HySTRA), which is carrying out the Japan-Australia pilot project, established the Policy on Health, Safety, Security and Environment (HSSE Effort) at its foundation, which incorporates security into the HSE concept. Based on this policy, Kawasaki has developed HSSE plans to specify the activities in our Kobe Works and Harima Works, which design and manufacture the liquefied hydrogen carriers and the liquefied hydrogen storage tanks. We are now implementing the activities specified in these HSSE management processes for the demonstration phase, based on the Plan-Do-Check-Action (PDCA) cycle.

Based on this project's plans, we are establishing our common HSE plan and management system that is also applicable to other projects. We are aiming for a more versatile, universal standard system in combination common and project-specific elements, and we will continue to make improvements while taking into account the results of actual projects.

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Conclusion

2020 and beyond, the demonstrations of the loading/unloading and marine transportation of liquefied hydrogen between the Hastings port in Australia and Kobe airport island in Japan, will have started, and we are working to complete all demonstrations without any accidents .

Finally, we would like to acknowledge the technical team of Shell Japan Ltd. for their enormous contributions to the safety assessments for this project.

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Kawasaki Heavy Industries Group

Main Products and Production Bases by Business Segment

Business Segment	Main Products	Main Production Bases
Ship & Offshore Structure	• LNG carriers, LPG carriers, crude oil carriers, bulk carriers, container ships, car carriers, high-speed vessels, submarines, ships for government and municipal offices	Kobe Works (Kobe, Hyogo Prefecture) Sakaide Works (Sakaide, Kagawa Prefecture) Kawasaki Subsea (UK) Limited (United Kingdom) Nantong COSCO KHI Ship Engineering Co., Ltd. (China)* Dalian COSCO KHI Ship Engineering Co., Ltd. (China)*
Rolling Stock	• Train cars, integrated transit systems	Hyogo Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Rail Car, Inc. (U.S.A.)
	• Rotary snowplows, deicing material spreaders • Railway motor cars, heavy-lift cars	NICHIJO CORPORATION. Akebono Plant (Sapporo, Hokkaido) Inaho Plant (Sapporo, Hokkaido)
Aerospace Systems	• Aircraft (fixed-wing aircraft and helicopters), missiles, electronic equipment, space systems and peripheral equipment, simulators	Gifu Works (Kakamigahara, Gifu Prefecture) Nagoya Works 1 (Yatomi, Aichi Prefecture) Nagoya Works 2 (Tobishima-mura, Aichi Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.)
	• Aircraft components, rocket components, space equipment, target systems • Aircraft servicing, remodeling	NIPPI Corporation Yokohama Plant (Yokohama, Kanagawa Prefecture) Atsugi Plant (Yamato, Kanagawa Prefecture)
	• Aircraft engines • Aircraft gear boxes	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
Energy System & Plant Engineering	• Cement, chemical, conveyers, and other industrial plant systems • Industrial boilers for land and marine use • Waste treatment facility • LNG tank and other storage facilities • Shield machines, tunnel boring machines	Harima Works (Harima-cho, Hyogo Prefecture) Anhui Conch Kawasaki Energy Conservation Equipment Manufacturing Co., Ltd. (China)* Anhui Conch Kawasaki Equipment Manufacturing Co., Ltd. (China)* Shanghai Conch Kawasaki Engineering Co., Ltd. (China)*
	• Gas turbine engines for ships, peripheral equipment • Gas turbine generators, gas turbine cogeneration systems	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
	• Steam turbines, diesel engines, gas engines, large decelerators • Marine propulsion systems (side thrusters, steerable thrusters) • Natural gas compression modules, air blowers and other aerodynamic machinery	Kobe Works (Kobe, Hyogo Prefecture) Harima Works (Harima-cho, Hyogo Prefecture) Wuhan Kawasaki Marine Machinery Co., Ltd. (China)
	• Air conditioning equipment, general-purpose boilers	Kawasaki Thermal Engineering Co., Ltd. Shiga Works (Kusatsu, Shiga Prefecture)
	• Crushers, recycling equipment and plant	EarthTechnica Co., Ltd. Yachiyo Works (Yachiyo, Chiba Prefecture)
Motorcycle & Engine	• Motorcycles, ATVs (all-terrain vehicles), recreational utility vehicles, utility vehicles, Jet Ski watercraft • General-purpose gasoline engines	Akashi Works (Akashi, Hyogo Prefecture) Kakogawa Works (Kakogawa, Hyogo Prefecture) Kawasaki Motors Manufacturing Corp., U.S.A. (U.S.A.) Kawasaki Motores do Brasil Ltda. (Brazil) India Kawasaki Motors Pvt. Ltd. (India) Kawasaki Motors Enterprise (Thailand) Co., Ltd. (Thailand) PT. Kawasaki Motor Indonesia (Indonesia) Kawasaki Motors (Phils.) Corporation (Philippines) Kawasaki Motores de Mexico S.A. de C.V. (Mexico) Changzhou Kawasaki and Kwang Yang Engine Co., Ltd. (China)* Bimota S.p.A. (Italy)
Precision Machinery & Robot	• Hydraulic equipment for construction machines, hydraulic equipment and systems for industrial machines • Marine application machines, deck cranes and other marine deck equipment • Industrial robots • Medical and pharmaceutical robots	Akashi Works (Akashi, Hyogo Prefecture) Nishi-Kobe Works (Kobe, Hyogo Prefecture) Kawasaki Precision Machinery (U.K.) Ltd. (U.K.) Kawasaki Precision Machinery (U.S.A.), Inc. (U.S.A.) Wipro Kawasaki Precision Machinery Private Limited (India) Kawasaki Precision Machinery (Suzhou) Ltd. (China) Kawasaki Chunhui Precision Machinery (Zhejiang) Ltd. (China) Kawasaki (Chongqing) Robotics Engineering Co., Ltd. (China) Flutek, Ltd. (Korea)
	• Hydraulic presses	Kawasaki Hydromechanics Corp. (Akashi, Hyogo Prefecture)

*Affiliated company-equity method

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