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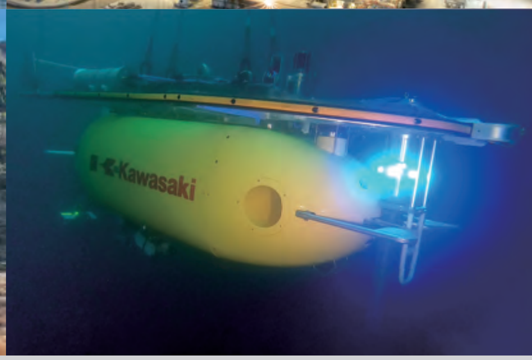
KAWASAKI TECHNICAL REVIEW

Special Issue on Energy Solution & Marine





TECHNICAL REVIEW

No.185
March 2024

Kawasaki Heavy Industries, Ltd.


Hydrogen and Carbon Neutral
Business Division
カワる、サキへ。
Kawasaki
Ship & Offshore Structure
Business Division
LH2
Contributing to Carbon Neutrality
without sacrificing convenience
Marine Machinery
Business Division
Kawasaki
Energy Solution
Business Division
Plant Engineering
Business Division

KAWASAKI TECHNICAL REVIEW

No.185

Special Issue on Energy Solution & Marine

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Energy and Marine Engineering: Business Updates and Future Developments

Motohiko Nishimura
Senior Managing Executive Officer
President, Energy Solution & Marine Engineering Company

Corporate mission

Energy Solution & Marine Engineering Company was established in April 2021 through a merger of Ship & Offshore Structure Company and Energy System and Plant Engineering Company. This coincided with the establishment of Hydrogen Strategy Division. This organizational restructuring is a shift toward the hydrogen business, which will form the basis of our future direction. This is a major step forward to contribute to the achievement of carbon neutrality to solve global warming, a societal issue faced by all of humankind.

In 2010, we declared our commitment to build a hydrogen supply chain, and since then, we have steadily completed the first such demonstration projects in the world, including the Kobe Smart Community Hydrogen Gas Turbine Cogeneration Project and the Liquefied Hydrogen Supply Chain Pilot Project between Australia and Japan (both projects are funded by NEDO: New Energy and Industrial Technology Development Organization, part of the Japanese government).

Currently, we are working diligently on a demonstration project for hydrogen commercialization. Its aim is to contribute to both carbon neutrality and energy security by supplying large quantities of hydrogen economically for full-scale commercial use in the early 2030s.

In this way, we have defined ourselves as an industry leader in hydrogen technology. In order to promote our hydrogen business, it is essential to secure profits from existing businesses related to general industry, public works, merchant ships, and naval ships, and we will continue to strive to improve the non-price competitiveness and profitability of our products.

Synergies generated by merger

Our products are supported by a wide range of unique technologies that are used in and on the sea, as well as on land and in space. Since the merger of the companies, we have achieved various forms of cross-functionality. These include shared design departments, sales, production, procurement, quality assurance, contracts, and commercial affairs, and we have furthermore pursued synergies of technologies and businesses among the divisions. Currently, we are promoting the skill diversification of our workforce and plants, and are working to build an organization that can respond quickly to the increased production of highly profitable products.

In order to commercialize our hydrogen business, we will gradually increase our annual production capacity. To this end, we will coordinate production at the Kobe, Harima, Sakaide, and Akashi Works. We will, for example, divide the production of vacuum insulated piping for liquefied hydrogen, onshore storage and marine cargo tanks, and other equipment for each component and part, and consolidate the final assembly in a single plant. This is where the aforementioned skill diversification of our workforce and plants will exhibit its true value.

Providing energy and environmental solutions

As an issue faced by customers moving towards carbon neutrality, the likelihood of stranded assets that have been using fossil fuels while emitting CO_2 is becoming a growing concern. Our gas turbines and gas engines, which boast the world's highest efficiency, are being developed so that we can provide "hydrogen ready" technology that can seamlessly respond to transitioning from our current use of natural gas to the future use of hydrogen. All models of gas turbines are already capable of 30 vol% co-firing of hydrogen, and some models can be freely switched between mono-combustion and co-firing of natural gas and hydrogen. There have already been projects in which our gas turbines have been sold with "hydrogen ready" being a recognized non-price value. As part of our preparation for carbon neutrality, we are also developing technologies for boilers that support hydrogen combustion.

Initiatives for a safe and secure remote society

The developed countries of the world are facing shortages in their working populations. As an island nation with a high language barrier, Japan's ability to rely on the employment of immigrants is limited. This is where Japan's leading robot technology comes into focus. We have been a leader in the business as the first robot manufacturer in Japan.

In the latest environmental plant (waste treatment facility) that we delivered to local municipalities, we have reduced the physical burden on workers and achieved labor savings by introducing robots for the sorting of recycled resources. In addition, we have introduced an AI-powered system that supports the operation of incinerators and are contributing to stable operations with support from the remote monitoring and support system KEEPER installed in our support center.

Closing comments

Through the achievement of a hydrogen-based society, we will contribute to maintaining and improving the convenience of daily life and achieving carbon neutrality, while providing reliable solutions to address social issues related to energy, environment, employment, safety, and more through a wide range of technologies and services.

Product and Technology Development in the Energy Solution & Marine Engineering Company

Keigo Imamura
Managing Executive Officer,
Vice President, Energy Solution & Marine Engineering Company and General Manager, Ship & Offshore Structure Business Division

Naoki Murakami
Executive Officer,
Vice President, Energy Solution & Marine Engineering Company

Introduction

The goals of our medium- and long-term business policy, Group Vision 2030, are to realize a hydrogen society and to achieve carbon neutrality. To attain these goals, in April 2021 we established Energy Solution & Marine Engineering Company by merging Energy System and Plant Engineering Company and Ship & Offshore Structure Company. The integration of these two companies has enabled us to build a system to provide solutions for production, transport, storage, and use, which are required to build hydrogen supply chains in a comprehensive manner. In addition, this integration has resulted in synergies such as interaction and sharing of expertise among our existing businesses including power generation, waste treatment, and shipbuilding. Merging companies is and will continue to be highly significant for us.

1 Introduction to the company

(1) Company overview

Energy Solution & Marine Engineering Company has five business divisions and four plants. The divisions are Hydrogen and Carbon Neutral Business Division, Energy Solution Business Division, Plant Engineering Business Division, Marine Machinery Business Division, and Ship & Offshore Structure Business Division. The plants are the Kobe Works, the Sakaide Works, the Harima Works, and the Akashi Works.

The products of the various divisions are as listed in **Fig. 1**. Our strength is our ability to meet various customer needs by combining the wide range of products we deal in to realize synergies.

(2) Hydrogen business

In the area of storage, Hydrogen and Carbon Neutral Business Division is in charge of liquefied hydrogen tanks and hydrogen terminals. In area of transport, Ship & Offshore Structure Business Division is in charge of liquefied hydrogen carriers. We are advancing projects related to these products, which are the core of the hydrogen commercialization demonstration to be described later, towards commercialization in 2030.

In the area of production, the Energy Solution Business Division and Hydrogen and Carbon Neutral Business Division are in charge of hydrogen compressors and hydrogen liquefaction equipment. In the area of use, Energy Solution Business Division is in charge of and develops hydrogen gas turbines, hydrogen gas engines, and hydrogen boilers, whereas Marine Machinery Business Division is in charge of and develops marine hydrogen gas engines and MHFS (Marine Hydrogen Fuel Systems).

We launched our hydrogen business ahead of other companies. We will collaborate with diverse stakeholders to realize a hydrogen society by leveraging the technologies and the expertise that we have accumulated.

(3) Optimization by leveraging a production system comprising four plants

We are building a system under which four plants mutually leverage their strengths and compensate for each other's weaknesses to achieve efficient production in light of corporate integration. In particular, the Kobe, Sakaide, and Harima Works are planning to divide the manufacturing of large liquefied hydrogen tanks and vacuum insulated piping and to work together in the hydrogen business. To

Division	Product family	Plant	Main products
Hydrogen and Carbon Neutral Business Division	Liquefied hydrogen terminals Low-temperature tanks	Kobe Harima	• Liquefaction • Shipping bases • Receiving bases • Low-temperature tanks (for liquefied hydrogen, LNG, etc.) • Hydrogen liquefaction equipment
Energy Solution Business Division	Energy systems	Kobe Akashi	• Industrial gas turbines • Gas engines for power generation • Aerodynamic machinery • Distributed energy systems
	Power plants	Kobe Harima	• CCPPs (Combined Cycle Power Plants) • Thermal power • Exhaust heat boilers • Steam turbines
Marine Machinery Business Division	Naval ship equipment Marine machinery	Kobe Akashi Harima	• Naval ship equipment • System-related equipment • Marine propulsion machinery • Marine reciprocating engines
Plant Engineering Business Division	Industrial machinery	Kobe Harima	• Delivery plants • Shield excavators • Ash treatment plants • Shredder plants
	Environmental plants	Kobe	• Waste treatment plants
Ship & Offshore Structure Business Division	Naval ships, special purpose ships and merchant ships	Kobe Sakaide	• Submarines • High-speed crafts • LPG/NH_3 carriers • Liquefied hydrogen carriers

Fig. 1 Main products and plants of each division

fully implement the hydrogen commercialization demonstration, production system optimization is the most critical issue.

We aim to achieve a system in which the four plants are operated in an integrated way to further harness the strengths of each plant and to enable flexible adjustment between off-time and on-time. We will first subdivide the production processes at each plant and visualize each plant's capabilities, features, and operating status. Based on the results, we will prepare production plans to realize an efficient production system.

In addition, we will standardize education at manufacturing sites in order to develop multiskilled workers so that each worker can be in charge of more processes. These workers will move among the four plants depending on which plants are busy. This will level out the operating rates, raising the capabilities of the manufacturing departments.

Aiming to realize robust plants that can properly address future changes in the business environment with agility, in addition to the hydrogen business, we will apply this system to existing businesses as well.

2 Hydrogen Commercialization Demonstration

As part of concrete efforts to realize a carbon neutral society, we are working on a demonstration of a commercial-scale hydrogen supply chain with Japan Suiso Energy, Ltd., utilizing the Green Innovation Fund Project (GI Fund) of the New Energy and Industrial Technology Development Organization (NEDO). We have already determined a candidate site. In FY2023, we will design a liquefied hydrogen carrier and start the FEED of liquefaction as well as shipping bases and receiving bases. Both the liquefied hydrogen carrier and the land liquefied hydrogen tank used in the commercialization demonstration will be large in scale; compared to a Japan-Australia pilot demonstration, the liquefied hydrogen carrier will have a load capacity 128 times larger, while the land liquefied hydrogen tank will have a storage capacity 20 times greater. To prepare for the use of multiple commercial chains, it is essential to achieve collaboration among the divisions and three plants, improvement of production capabilities, and streamlining for lead time reduction. Our current activities include efforts to establish a system in which three plants divide the manufacturing of 10,000-m^3 spherical tanks and vacuum insulated piping for liquefied hydrogen shipping bases as well as efforts to develop manufacturing and inspection technologies, including automation and modularization construction methods. For the liquefied hydrogen carrier, we are making progress in processes, including verification of manufacturability and performance using a test tank as well as development of a hydrogen-powered propulsion system.

(1) Establishing a three-plant manufacturing system for 10,000-m^3 spherical tanks

We plan to construct five 10,000-m^3 spherical liquefied hydrogen tanks at the liquefied hydrogen shipping base and have built a general management system for the Harima Works, Kobe Works, and Sakaide Works to divide the manufacturing of these tanks.

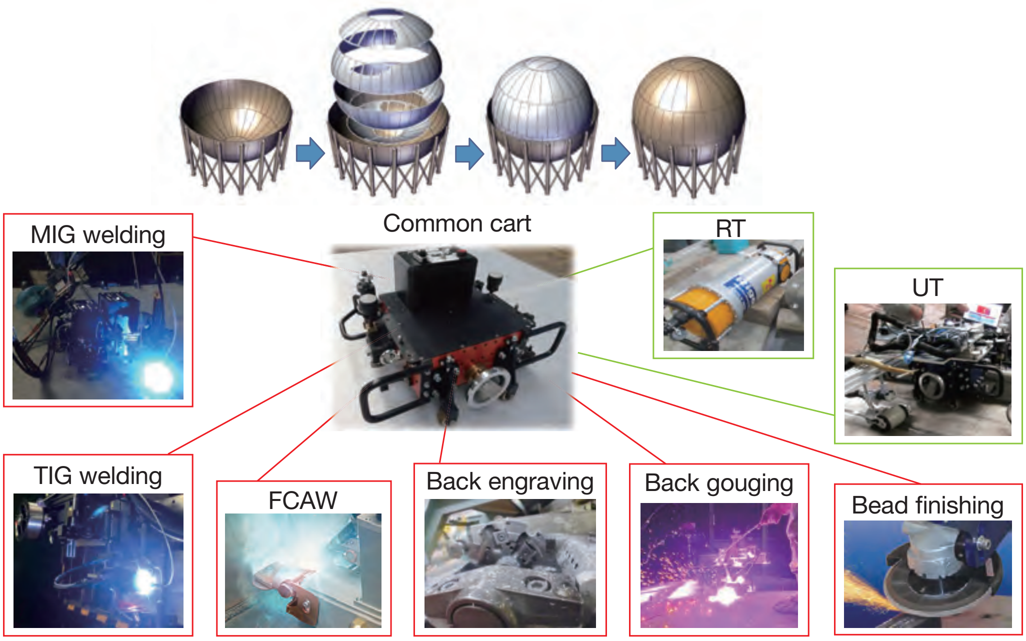


Fig. 2 Image diagram of technologies for improving the efficiency of the spherical tank module construction method

In particular, we have clarified the scopes of responsibility at the interfaces between the plants, defined procedures for transferring and managing necessary information, and built a mechanism for seamless operations.

We have also developed a construction method to finish the tanks at our three plants in Japan and to transport the finished tanks by ship in order to achieve advanced modularization and reduce delivery times, which are critical for conforming to processes in contracts for overseas construction work. In particular, the Sakaide and Kobe Works have also acquired ASME certification based on the Harima Works' experience acquiring the certification. To improve the efficiency of plant manufacturing, we have developed plate bending, cutting, and grooving methods as well as self-propelled automatic MIG/TIG welders and an automatic UT device. In addition, we have developed a safe marine transport method using barges and a method for realizing safe carry-in to shipping bases.

(2) Liquefied hydrogen carrier

Leveraging insights obtained from the Suiso Frontier, a world-first 1,250-m^3 liquefied hydrogen carrier that we constructed, Ship & Offshore Structure Business Division is developing the basic design for a large liquefied hydrogen carrier with a cargo capacity of 160,000 m^3, which is 128 times greater than the Suiso Frontier. We plan to complete construction of this carrier during the late 2020s and demonstrate long-distance mass transport of liquefied hydrogen.

As its propulsion system, this carrier employs a steam turbine plant consisting of a main boiler and a main turbine. Steam generated in the main boiler drives the main turbine, the force of which is transmitted to the propellers via the reduction gear in order to propel the carrier. The main boiler can be operated by hydrogen only, oil only, or hydrogen/oil mixed firing. Notably, this boiler achieves zero greenhouse gas (GHG) emissions when operated by hydrogen only. In this carrier, we also plan to install a dual fuel generator engine that can switch between hydrogen and oil for demonstration purposes.

Energy Solution Business Division is developing and designing the main boiler, main turbine, and dual fuel generator engine while developing the hydrogen-powered propulsion system in collaboration with Ship & Offshore Structure Business Division. We also plan to standardize and normalize the technologies.

3 Hydrogen and Carbon Neutral Business Division

On August 1, 2023, we carried out an organizational restructuring to efficiently and reliably execute carbon neutrality projects, and established Hydrogen and Carbon Neutral Business Division.

For hydrogen-related products, this division is in charge of liquefaction and loading terminals and unloading terminals, and it provides liquefied hydrogen tanks as its core product. The division is working to implement the hydrogen supply chain commercialization demonstration.

4 Energy Solution Business Division

The Energy Solution Business Division is in charge of hydrogen gas turbines, hydrogen gas engines for power generation, hydrogen boilers, and hydrogen compressors in the hydrogen business. The division is also developing CO_2 capture equipment towards the realization of a carbon neutral, carbon recycling society and has started a demonstration test in Japan.

(1) Hydrogen gas turbines

We have developed hydrogen gas turbines and hydrogen gas engines with hydrogen mixed firing and hydrogen combustion ahead of other companies in order to seamlessly support the transitional period from the start of hydrogen use up to the dawn of a full-fledged hydrogen society. For gas turbines, we have already established and started sale of a hydrogen mixed firing combustion technology. As for hydrogen combustors, we have completed the development and demonstration of some models and are working to deploy them across the entire lineup. Our hydrogen gas turbines enable existing natural gas generators to support hydrogen without needing to make significant alterations. We have already received orders for projects predicated on alteration to enable hydrogen support in Europe and for projects predicated on future hydrogen support in Japan.

(2) Hydrogen compressors

The high-efficiency centrifugal hydrogen compressor is equipment that is essential for increasing the size of hydrogen liquefiers and improving their liquefication efficiency. We developed this equipment, which was selected for a GI Fund project as a product required to achieve the target hydrogen supply cost in 2050. We plan to test and evaluate various element technologies by the end of FY2022, to create prototypes in FY2023, and to start operation in plants during FY2024. We will then increase the size and implement additional innovative technologies toward 2030. As high-efficiency centrifugal hydrogen compressors can be used not just in hydrogen liquefiers but in a wide range of applications, such as hydrogen pipelines and hydrogen fuel gas supply, we plan to launch products starting with frontier markets.

(3) CO_2 capture technologies

As CO_2 capture technologies are positioned as required elements in the "Roadmap for Carbon Recycling Technologies" created by the Ministry of Economy, Trade, and Industry, we have developed a CO_2 capture technology that employs the solid sorption method and started demonstration tests. In Japan, we have installed demonstration equipment at coal-fired power plants and elsewhere to start demonstration tests in order to evaluate applicability to coal combustion exhaust gas. We are also constructing demonstration equipment at the Dry Fork Power Plant in Wyoming in the U.S. We plan to monitor the environment of the surrounding region while capturing CO_2.

5 Plant Engineering Business Division

The Plant Engineering Business Division has thus far delivered social infrastructure equipment such as cement plants, fertilizer plants, handling systems, LNG tanks, and municipal waste treatment facilities. Upon the establishment of Hydrogen and Carbon Neutral Business Division in August 2023, key persons were assigned to it in order to build hydrogen supply chains by reliably leveraging the technologies we have accumulated through our hard-won experience. Meanwhile, Plant Engineering Business Division is developing businesses in the area of material recycling as well as developing labor-saving technologies for municipal waste treatment and other facilities.

Fig. 3 Recycling system for lithium-ion batteries

(1) Material recycling

Combustion ash generated when solid fuels are burned contains unburned carbon, which ought to have been combusted. Unburned carbon not only leads to energy loss but also hinders ash recycling. We have developed a dry processing system and equipment to remove unburned carbon in order to promote recycling and have received orders for commercial application.

In addition, we are developing lithium recycling technologies for lithium-ion batteries, the use of which is expected to increase. We are currently conducting a demonstration test in China.

(2) Labor-saving technologies

Responding to Japan's shrinking workforce is an urgent issue both in waste treatment facilities and recycling facilities. This issue must be addressed while considering how to guarantee safety and reliability as well as how to reduce operator workloads. Against this background, we have developed labor-saving operation technologies, including K-Repros, an AI-powered support system for hand-sorting recyclable waste.

We have also developed and launched the robot system Successor-G, which automatically performs remote operation of grinders in harsh environments exposed to powder dust and sparks.

We will continue to develop labor-saving technologies and broaden the range of applications.

6 Marine Machinery Business Division

The business of Marine Machinery Business Division encompasses a wide lineup, including core components of propulsion systems for commercial ships and naval ships as well as system package products.

(1) Marine reciprocating engines

We have produced and delivered two-stroke and four-stroke reciprocating engines for over 110 years since 1911, when we began a technology partnership with MAN in Germany. In 2014, we developed the L30KG gas combustion engine as a private brand by leveraging our accumulated technologies. In response to increasing demand for GHG emissions reduction, we are focusing on LNG- and LPG-fueled gas engines, and we have started development of marine hydrogen gas engines to achieve carbon neutrality.

(2) Marine propulsion machinery

Over the years, we have delivered many propellers; our lineup includes controllable pitch propellers, side thrusters, and the Rexpeller azimuth thruster. We have expanded our business by sophisticating technologies with controllable pitch propellers, which require high propulsion performance, and expanding the application of these technologies to side and azimuth thrusters. In particular, we increased the number of delivered side thrusters mainly for container ships and have the highest global share as of 2022.

(3) Package products and system integration

As needs for package products, which combine a variety of components, and system integrators, which realize such products, have increased recently, we are working to integrate various propulsion systems, including environmentally friendly propulsion systems for

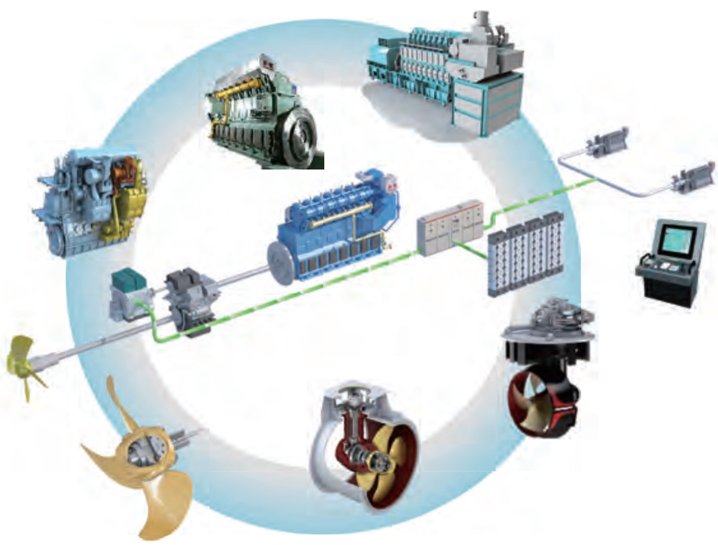


Fig. 4 Marine propulsion system products

commercial ships and hybrid propulsion systems for naval ships. In 2022, we delivered a battery propulsion system that is exclusively battery-powered; in 2023, we delivered a hybrid propulsion system that combines the L30KG gas engine with batteries.

We have also delivered the KICS integrated control system to operate propellers, rudders, and other equipment in an integrated manner for ferries, cable ships, and other vehicles. Needs for safety and manpower reduction have been increasing recently. In particular, there is demand for safety and crew manpower reduction during ship berthing/unberthing. Against this background, we have begun to develop a safe berthing/unberthing assist system based on our KICS technologies.

7 Ship & Offshore Structure Business Division

The main products of Ship & Offshore Structure Business Division are submarines and their product families based on related technologies, and merchant ships, especially focused on liquefied gas carriers.

(1) Submarines and related products

We have delivered a total of 30 submarines, including Oyashio, the first domestic submarine after World War II that was completed in 1960, and Hakugei, a state-of-the-art submarine. The new-type submarine has a long underwater endurance capability enabled by lithium-ion batteries and adopts leading-edge technologies, for example, a variety of automation systems as well as improved/increased surveillance and stealth capabilities. We have also developed products including SPICE, autonomous underwater vehicle, which uses underwater technologies we have accumulated by building submarines over the years, and new products for terrestrial use that are based on CO_2 capture technology used in submarines, which are closed spaces.

(2) Merchant ships

We have continued to provide high-quality ships based on cryogenic liquefied gas technologies ever since we delivered our first liquefied petroleum gas carrier (LPG carrier) in 1969 and our first liquefied natural gas carrier (LNG carrier) in 1981. As alternative fuels with low GHG emissions have recently been adopted one after the other around the world, our first LPG-fueled cargo ship in Japan is highly recognized by customers and we get continuous orders for the following ships. In addition, we have received numerous shipbuilding orders that incorporate new environmentally-friendly technologies, including LNG-/methanol-fueled ships, and we have built them through joint venture shipyards in China, thereby maintaining high competitiveness.

In addition, we constructed the world's first liquefied hydrogen carrier by integrating shipbuilding technologies for liquefied gas carriers and in-house liquefied hydrogen technologies described above, and we completed a demonstration of liquefied hydrogen transportation by ship. As our next challenges, we are working to ensure stable mass supply of liquefied hydrogen and to enlarge the size of ships to achieve the reduction of transportation costs.

(3) Others

SOPass, ship operation support service, which leverages our insights into shipbuilding and cryogenic liquefied gas technology for the engineering of LNG carriers, has been recognized as valuable by customers who have introduced the service (mainly charterers of LNG carriers). We continue to enhance the functionality of the service to further optimize operations and reduce GHG emissions.

In addition, in 2020 we delivered our JETFOIL for the first time in 25 years. This is an ultra-high-speed passenger hydrofoil and flies over the water surface by dynamic lift generated by fully-submerged foils. JETFOIL plays an active part as essential infrastructure of transformation for remote islands in Japan. It is expected to contribute to society because momentum for constructing additional ships has been rising following the 2022 revision of the Japanese Remote Islands Development Act.

Conclusion

The Energy Solution & Marine Engineering Company has built a system to provide solutions for hydrogen supply chains in a comprehensive manner. We will contribute to realizing a hydrogen society and achieving carbon neutrality.

In addition, the company will realize synergies among Hydrogen and Carbon Neutral Business Division, Energy Solution Business Division, Plant Engineering Business Division, Marine Machinery Business Division, and Ship & Offshore Structure Business Division as well as the Kobe Works, the Sakaide Works, the Harima Works, and the Akashi Works in order to provide a wide range of products that meet customers' various needs.

We are committed to supporting a prosperous global society and contributing to the preservation of the global environment as a company that plays an important role in "ensuring a safe, secure, remote society" and "energy and environmental solutions" according to the future focus fields defined in our Group Vision 2030.

World's Most Efficient 5MW-Class Gas Turbine, M5A

Under the Paris Agreement, which is a framework aimed at mitigating global warming, promoting cogeneration (combined heat and power application) is increasingly important for realizing a low-carbon society. In particular, gas turbine cogeneration, which enables the utilization of high-temperature steam, is expected to further boost efficiency.

By combining state-of–the-art technologies with Kawasaki's expertise in gas turbines and extensive experience in this field, all the elements are optimized through flow analysis and measured and evaluated the vibration of all the rotor blades in a contactless fashion. M5A was also successfully developed, which is a cogeneration gas turbine with the world's highest efficiency in the 5MW class and reduced NOx emissions. M5A has been adopted in 15 domestic and overseas sites, and the total operation time has exceeded 160,000 hours.

Introduction

Under the Paris Agreement, which is a framework aimed at mitigating global warming, cogeneration is increasingly implemented to realize a low-carbon society because its value as a distributed energy system is appreciated in terms of not only energy savings and CO_2 emissions reductions but also stable electricity supply. In addition, the market has become active as a result of institutional reforms such as liberalization of the electricity and gas retail markets as well as profitability improvement through the development of new technologies. In particular, gas turbine cogeneration, which enables the utilization of high-temperature steam, has been widely implemented mainly in industrial areas, and further efficiency improvement of gas turbines is expected.

1 Background

Since the 1983 market launch of our 1MW-class cogeneration system that employed our proprietary gas turbine, we have built a lineup that includes 30MW-class models to satisfy various market demands. We developed the GPB50D cogeneration system, which is mainly composed of our 5MW-class M5A gas turbine and main unit. The M5A gas turbine realizes best-in-class efficiency and environmental performance by combining the industrial gas turbine development technologies we have accumulated over the years with state-of-the-art technologies while ensuring reliability based on our deep experience and track record [1)].

2 Development concept

We developed the M5A gas turbine as a new model that fills the gap in our lineup between the compact M1A and the medium-sized M7A in order to provide an excellent system to satisfy diversifying demands. **Fig. 1** is a bird's eye view, while **Table 1** lists the main specifications. The features are described below.

(1) Remarkable cogeneration performance

The thermal efficiency of this gas turbine is peerless among 5MW-class gas turbines, exceeding even the trend set by the latest high efficiency models. At the same time, the exhaust gas is set to a suitable temperature for exhaust heat recovery to achieve high overall efficiency.

To ensure the durability of hot sections, the turbine inlet is set to a moderate temperature. The amount of cooling air is reduced to decrease power loss. In addition, we have eliminated issues stemming from its small size and realized both a large operating range and high efficiency; we achieved this by, for example, applying optimization design technology using state-of–the-art flow

† A gas turbine for which we have realized best-in-class power generation efficiency and environmental performance by combining technologies for industrial small- and medium-sized gas turbines accumulated over the years and by applying state-of–the-art technologies, all the while maintaining reliability based on our deep experiences and track record

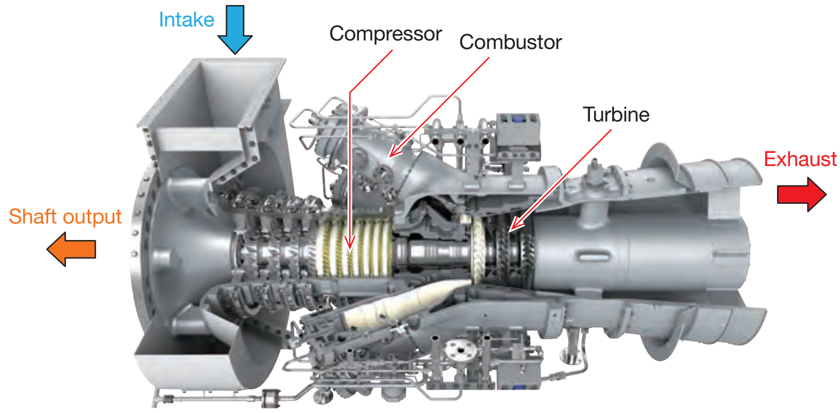


Fig. 1 Bird's eye view of M5A gas turbine

Table 1 Main specifications of M5A gas turbine

Type	Simple open cycle, single shaft
Compressor	Axial 11 stages
Turbine	Axial 3 stages
Combustor	6 cans
Dimensions [m]	L2. 6×H1. 5×W1. 4
Electric output [MW]	4. 96
Thermal efficiency (LHV standard) [%]	33. 0
Exhaust mass flow [kg/s]	17. 6
Exhaust temperature [°C]	523
Emissions	NOx：52. 5ppm or less（O_2=0%）

※ ISO conditions, no inlet/exhaust pressure loss, 100% CH_4

analysis to every aerodynamic element and adopting a bowed blade as the stator vane at the compressor rear stage.

(2) Best-in-class environmental performance (low NOx)

This gas turbine is equipped with our proprietary pilot, main, and supplemental fuel nozzles. It includes a six-can dry low emission combustor (hereafter referred to as a DLE combustor) that employs the time-proven lean premix combustion method. The gas turbine controls the fuel flow to each fuel nozzle according to the operating status in order to maintain the optimal combustion state and to achieve the highest level of environmental performance (low NOx) in the 5MW class across a wide operating range.

(3) Continuing the reliability of the M1A and M7A gas turbines

During development design, we made it a top priority to ensure the same level of reliability as the time-proven M1A and M7A gas turbines. We also resolved to realize performance and other features at high levels. To do so, we used a proven structure and materials with established quality to achieve overall optimization of characteristics such as functionality, weight, size, maintainability, and operability.

(4) Light weight and compact

We significantly reduced the size while constraining pressure loss by adopting a simple ring casing structure from the M1A gas turbine and applying optimization design based on the most advanced flow analysis to the intake and exhaust flow paths. This resulted in a smaller generator enclosure.

(5) Long maintenance and inspection cycle

To ensure continuous operation, gas turbine maintenance includes an annual bore scope inspection and a quadrennial overhaul. For the overhaul, the existing gas turbine is exchanged with a refurbished one to reduce the maintenance downtime.

(6) Outstanding operability

It just takes 10 minutes for the gas turbine only to start and reach rated output, excluding the time for pre-purging. In addition, the gas turbine supports DLE operation in which it operates with low emissions even during island-operation while delinked from the grid system. This enables the system to tolerate a maximum load rate of 50% even if the load suddenly changes during island-operation, thus realizing outstanding operability.

(7) Performance improvement by leveraging a higher temperature tolerance

Our verification test for long-term reliability using multiple commercial M5A gas turbines confirmed that the hot parts can tolerate higher temperatures. This enabled us to make improvements by raising the operating temperature to harness the potential for performance improvement without making significant design changes.

3 Development program

Aiming for rapid development and a seamless market launch with ambitious development goals, we started a development project in April 2014. We carried out product planning, gas turbine design, and production preparations simultaneously. We started an operation test of the gas turbine in December 2016; completed the series of necessary verifications, including performance and integrity assessment and an endurance test, through an internal operation test that lasted slightly under a year; and completed initial development in October 2017. Then, after conducting a preliminary test to support higher temperatures and assessing the additional overhaul inspection results of commercial M5A gas turbines and other factors, we started a performance improvement project in 2019, which took two years to complete.

After verifying performance and integrity during a development test, we operated the gas turbines under various harsh conditions during an endurance test; we then conducted an inspection and check. When improvement design was necessary, we returned to an upstream process and conducted the tests and assessment again. By preparing for the possibility of this rework in advance and breaking down measurement into detailed measurement and durability/performance measurement using two prototype gas turbines to conduct tests efficiently, we succeeded in completing the tests rapidly.

To check reliability, we used all our expertise that we accumulated through the development of the L30A gas turbine, such as a non-contact blade vibration measurement technology for rotor blades at all stages of the compressor and turbine and a blade surface temperature measurement technology using a pyrometer for rotor blades at all stages of the turbine, for the tests and assessments. We conducted real-time processing and analysis for timely assessment and evaluation, acquiring data on operation test equipment and measuring over 1,000 items in a monitoring system. Typical measurement examples are described below.

(1) Compressor

It is essential to assess the high cycle fatigue of blades because they undergo aerodynamic excitation due to causes such as the wake generated by the front vane. Therefore, we conducted optical non-contact blade vibration measurement for all rotor blades. We captured changes due to blade vibration when the blades passed through a sensor, assessed the vibration, and confirmed integrity through an endurance test. In addition, we are working to apply measurement probes made using additive manufacturing.

(2) Combustor

We assessed amplitude and frequency by measuring pressure fluctuations using a semi-conductor pressure transducer to check combustion oscillation during lean premix combustion. In addition, we used thermocouples and thermal paint together to confirm that the temperature allows for parts durability to be maintained.

(3) Turbine

We applied a pyrometer with superior temperature resolution [2)] to assess the temperature of turbine rotor blades (**Fig. 2**). At the same time, we verified the accuracy assessment that employs thermocouples using a slipring. We also measured the vibration of rotor blades using a gauge during this measurement to assess high cycle fatigue together with separately conducted non-contact blade vibration measurement at the blade tip gaps.

(4) Structure

For the intake and exhaust flow paths designed to be smaller than those of conventional models, we measured the static pressure on the wall surface of each section and the total pressure; we conducted the flow analysis shown in **Fig. 3** for assessment, and confirmed that the paths provide the expected performance.

Despite the short development period, we enhanced product reliability by conducting thorough quantitative assessment as illustrated above during an actual turbine operation test. Meanwhile, we quantitatively recognized the product's potential for better merchantability and room for further performance improvements.

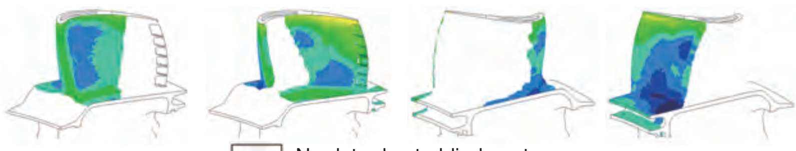


Fig. 2 Results of temperature measurement of turbine rotor blades with pyrometer

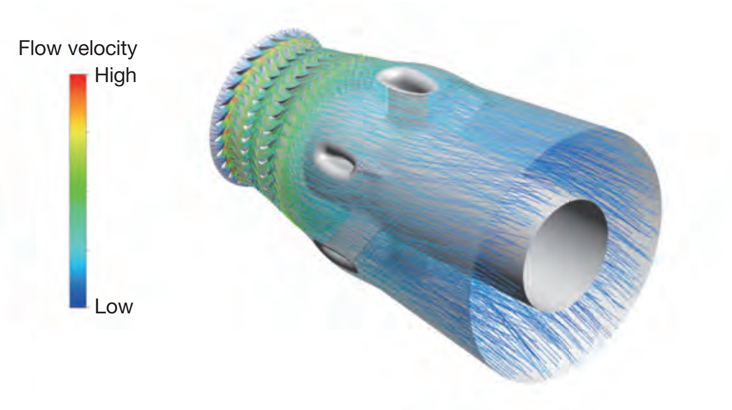


Fig.3 Example of flow analysis of exhaust flow path

4 GPB50D Cogeneration system

Table 2 describes the performance of the GPB50D Kawasaki gas turbine cogeneration system, which employs the M5A gas turbine as its core component in combination with an heat recovery steam generator and other components. The thermal efficiency is higher than that of gas turbines in the same class by about 3 points (32.3%), and the total efficiency is higher by about 3 points (85.3%), thus providing high economic efficiency. The NOx value of this system offers best-in-class environmental performance.

As a typical example, the GPB50D for domestic can reduce energy consumption by 20.9% and CO_2 emissions by 17.5% compared to conventional systems, which use commercial electricity and a gas boiler. Moreover, energy costs are expected to be reduced by about 350 million yen a year compared to conventional systems under conditions such as a purchased electricity cost of 20 yen/kWh and a city gas cost of 100 yen/m^3N.

Table 2 Cogeneration performance of GPB50D

Model	「GPB50D」
Gas turbine model	「M5A-01D」
Electric output [kW]	4, 685
Fuel consumption [Nm^3/h]	1, 287
Steam mass flow [kg/h]	10, 980
Thermal efficiency [%]	32. 3
Heat recovery efficiency [%]	53. 0
Total efficiency [%]	85. 3
NOx value（O_2 = 0%）（DLE operating range）[ppm]	52. 5（50% to 100% load）

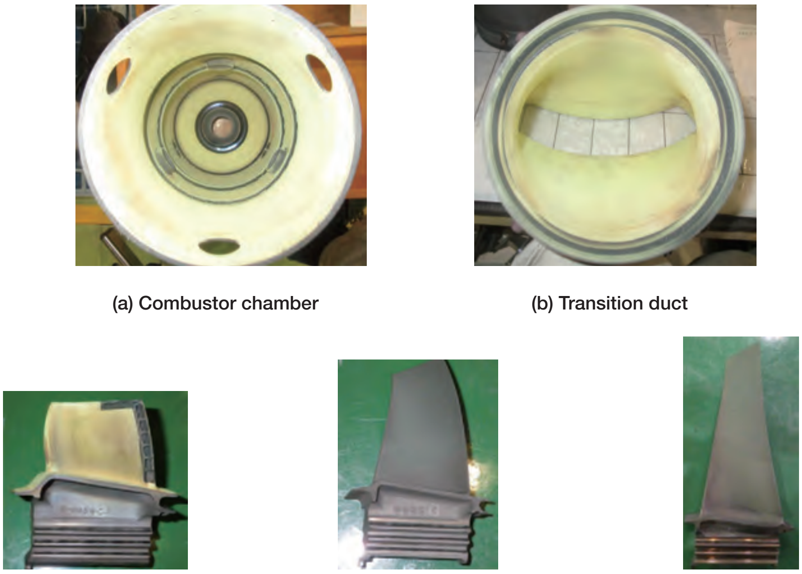
Intake temperature: 15°C, atmospheric pressure: 101. 3 kPa（at an altitude of 0 m）
Intake/exhaust pressure loss: 0. 98/2. 94 kPa
Fuel: City gas 13A
Heat recovery steam generator: Steam pressure of 0. 78 MPaG, supply water temperature of 60°C

5 Operation experience

The first model delivered to a domestic user started commercial operation in July 2018. In this project, we upgraded an existing gas turbine cogeneration system having lower economic efficiency and environmental performance with a new model. We reused the existing system to the extent possible, including the foundation, accessories, stack, and electrical equipment.

After about three years had elapsed since the start of operation, we conducted an additional overhaul inspection of the gas turbine. The gas turbine was brought back from the site, completely disassembled it at our factory, and conducted a visual inspection, dimensional inspection, and non-destructive inspection. To assess long-term durability, we reassembled the gas turbine without replacing any parts except for some samples taken during the destructive inspection, and returned it to the customer's site for continued operation.

Fig. 4 shows photographs of combustor parts and turbine rotor blades during a factory inspection. All parts were in very good condition, and no harmful defects were found. We confirmed rubbing was not excessive but rather moderate at the blade tips and the clearance of the labyrinth seal section, and we demonstrated that three-year operation poses no issues in terms of durability and



(a) Combustor chamber (b) Transition duct

(c) 1st-stage rotor blade (d) 2nd-stage rotor blade (e) 3rd-stage rotor blade

Fig.4 Example of hot gas path parts at additional overhaul inspection at factory

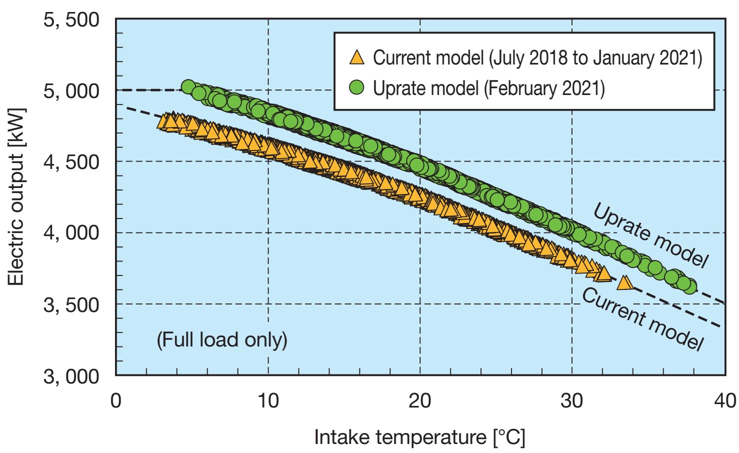


Fig. 5 Trends in performance after application of M5A gas turbine with uprate performance

stability.

After this additional overhaul inspection, the user introduced the M5A gas turbine with uprate performance. The gas turbine has achieved the planned performance as shown in **Fig. 5**, and features such as fuel consumption and steam amount did not deteriorate during operation. Going forward, we will accumulate actual operation cases, continue to observe progress through planned inspections, and demonstrate reliability by assessing long-term durability and stability.

Conclusion

We expect that the M5A gas turbine with outstanding features such as worldwide best-in-class efficiency and environmental performance will drive cogeneration implementation in light of policy support for CO_2 emissions reduction and rising awareness regarding business continuity through energy supply in emergencies. We will also continue to further improve merchantability to contribute to solving energy and environmental issues around the world.

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Energy-Saving CO_2 Capture System KCC

As an effort toward decarbonization, the demand for CO_2 capture is increasing. However, reducing its cost is a technical challenge to popularizing CO_2 capture. Therefore, we are developing KCC (Kawasaki CO_2 Capture), which is an energy-saving CO_2 capture system that is expected to drastically reduce the energy required to capture CO_2 with the solid sorbent method.

Introduction

Reflecting the Paris Agreement adopted at the 21st Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP21), the world is striving to reduce CO_2 emissions to net zero, and there is an urgent need to formulate and implement concrete plans to achieve this goal. Throughout this process, much attention has been placed on maximum deployment of renewable energy, but thermal power generation retains an important function as a flexible means for accommodating for the variability of renewable energy, so decarbonization of thermal power generation is needed.

1 Background

To decarbonize thermal power generation, research and development is underway to change the fuel used to hydrogen or ammonia; meanwhile, installation of CO_2 capture facilities offers the advantage of enabling existing fuel procurement systems and facilities to continue to be used to permanently store CO_2, thereby helping to reduce CO_2 emissions. On the other hand, for unavoidable CO_2 emissions, industrial technologies that can achieve negative emissions are needed, such as Direct Air Carbon dioxide Capture and Storage (DACCS), which captures CO_2 directly from the atmosphere and permanently stores it, and Bioenergy with Carbon dioxide Capture and Storage (BECCS), which captures CO_2 from the flue gas of biofuel combustion and permanently stores it. Demand is growing for such CO_2 capture facilities as a focus of decarbonization efforts, but technological challenges remain, including cost reduction.

2 Emission reduction targets and efforts by country

Based on a recognition that reducing CO_2 emissions is a common challenge for humanity, various CO_2 emission reduction targets have been announced. In particular, the International Energy Agency (IEA) Net Zero Emissions by 2050 (NZE2050) sets specific targets as scenarios for achieving net zero CO_2 emissions from energy use and industrial processes worldwide. Among these scenarios, the expected reductions from CO_2 capture are estimated to be about 7.6 Gt-CO_2/year in 2050 [1), as shown in **Fig. 1**.

In Europe, the EU Emissions Trading System (EU ETS), a decarbonization initiative, was launched in January 2005. The EU ETS has been revised as necessary, and a notable change for phase 4, which stretches from 2021 to 2030, is an agreement to introduce a Carbon Border Adjustment Mechanism (CBAM). The CBAM is intended to prevent industrial out-migration and consequent carbon leakage to non-EU countries by closing the carbon cost gap between EU products and products imported into EU markets; it is in effect a carbon border tariff. Another notable point is that the auction revenues from the fee-based allocation of

	2020	2030	2050
1. CO_2 captured from fossil fuels			
Power sector	0. 03	3. 40	8. 60
Industrial sector	0. 03	3. 60	26. 20
Hydrogen production sector	0. 03	4. 55	13. 55
Non-biofuels production sector	0. 30	1. 70	4. 10
Subtotal	0. 39	13. 25	52. 45
2. CO_2 captured from bioenergy			
Power sector	0. 00	0. 90	5. 70
Industrial sector	0. 00	0. 15	1. 80
Biofuels production sector	0. 01	1. 50	6. 25
Subtotal	0. 01	2. 55	13. 75
3. Direct Air Capture (DAC)			
Utilization	0. 00	0. 20	3. 55
Permanent Storage	0. 00	0. 70	6. 30
Subtotal	0. 00	0. 90	9. 85
Total [Gt-CO_2/year]	0. 40	16. 70	76. 05

Fig. 1 CO_2 capture scenario (Source: IEA NZE2050)

EU ETS allowances will be invested in a fund to tackle climate change. This innovation fund will support investment in innovative low-carbon technologies, such as Carbon dioxide Capture, Utilization and Storage (CCUS); renewable energy; and energy storage. The carbon price of EU ETS carbon futures exceeds 100 EUR/t-CO_2 for the first time in February 2023, and it indicates that Europe has strong investment potential.

In the U.S., the Infrastructure Investment and Jobs Act was further strengthened in 2022 with the passage of the Inflation Reduction Act (IRA), which introduced significant tax credit incentives for carbon-free energy and clean technologies, including renewables, hydrogen, CCUS, and DAC. Under the IRA, CCUS is eligible for large tax credits of $85/t-$CO_2$ for permanent storage and $60/t-$CO_2$ for utilization. DAC is eligible for tax credits of $180/t-$CO_2$ for permanent storage and $130/t-$CO_2$ for utilization. These tax credits have an enormous impact and make DAC a realistic investment prospect rather than a pipe dream. As shown in **Fig. 2**, the U.S. has one of the largest carbon reservoirs in the world; thus, the IRA significant impacts the global decarbonization trend.

In Japan, discussions regarding the commercialization of domestic CCS projects have begun, and an emissions trading market is expected to be established through the GX (Green Transformation) League. In addition, the

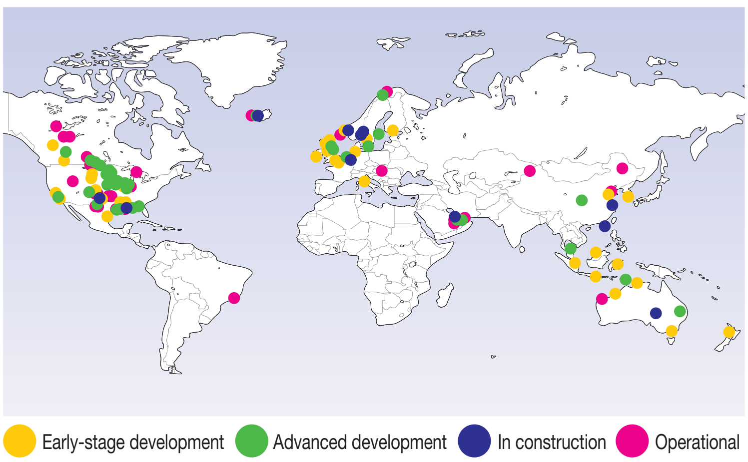

Fig. 2 Global CCS projects [2)]
Source: Based on GCCSI's "Global Status of CCS 2022"

government is actively supporting the development of CCS through the Green Innovation Fund and other grants, and, with the aim of reducing emissions, development efforts to achieve social implementation of CCS, along with hydrogen, are progressing.

In this way, CO_2 capture, storage, and utilization are attracting attention as clean technologies that lead to decarbonization, and they are influencing countries' policies as a realistic solution to reduce emissions. To further promote the global deployment of CO_2 capture facilities, which will be a key technology for decarbonization, the cost of CO_2 capture must be further reduced below that of current technologies through the development of innovative low-carbon technologies.

3 CO_2 capture technologies

(1) Conventional technologies

The solvent process is the well-known commercially available process for capturing CO_2 from flue gases.

In the solvent process, depending on the target gas, an amine- or potassium-based aqueous solution is used as the CO_2 absorbent. When in contact with a CO_2-containing gas, the aqueous solution absorbs the CO_2 in the gas, thereby separating the CO_2 from the gas. The CO_2-containing aqueous solution is then heated to separate and recover the CO_2. This heating process requires the energy of not only the bond dissociation energy between CO_2 and amine but also latent and the sensible heat of water due to the accompanying of moisture to recover CO_2 from the aqueous solution, which consumes a large amount of thermal energy.

(2) Amine-impregnated solid absorption method

To reduce the energy consumption of CO_2 separation, which is challenging with the conventional amine solvent method, we are developing the KCC (Kawasaki CO_2 Capture) process using a solid sorbent, which originated from our technology research for removing CO_2 from the air in closed spaces such as submarines. As shown in **Fig. 3**, our developed solid sorbent is a porous support material coated with an CO_2-absorbing amine on its surface.

Since unlike the conventional solvent method, our solid sorbent separates CO_2 using only the energy of the low-temperature steam, it does not require energy from the latent heat of water, resulting in an approximately 60% reduction in energy use for CO_2 capture compared to the conventional method. Furthermore, with this amine-impregnated solid absorption method, the amine is less volatile than the amine used in the solvent method, which reduces the amount of amine dispersed outside the process system and thus lowers the environmental impact.

4 CO_2 capture systems

We have developed two systems that use this solid sorbent for post-combustion flue gas and ambient air: a fixed bed system and a moving bed system.

(1) Fixed bed system

In the fixed-bed system, the solid sorbent is fixed in a tower, and three processes are batch-wise switched among multiple towers. These three processes are the absorption process to absorb CO_2, the desorption process to desorb CO_2 with steam, and the drying process to dry the moisture absorbed from the steam. This system offers a simple plant configuration and is suitable for small-scale CO_2 capture plants intended for testing and evaluation.

Making the most of such plant features, we will conduct an environmental impact assessment test of our developed amine-impregnated solid sorbent in Wyoming in the United States. This test will be implemented under a project of the Japanese Ministry of the Environment entitled "Development Project of Integrated Demonstration Facility and Supply Chain for Sustainable CCUS (CO_2 Capture Technology Demonstration with Solid

Fig. 3 Amine-impregnated solid sorbent

Absorbent)" together with the project leader, the Japan Carbon Frontier Organization (JCOAL). This project is a Japan-U.S. collaboration to construct a demonstration test plant for CO_2 capture technology that will be built at the Integrated Test Center (ITC) adjacent to Dry Fork Station (a pulverized coal-fired power plant) in Wyoming. Tests will be conducted using actual flue gas from the power plant.

In Europe and the United States, there are growing concerns about the effects on living organisms of amine emissions from the amine-based aqueous solution released into the environment during the CO_2 capture process. In this project, in accordance with relevant environmental impact assessment methods, we will conduct analysis of the exhaust gas released from our test plant after the CO_2 capture process as well as conduct environmental monitoring and analysis of amine-containing discharges in the surrounding areas before, during, and after the test period in FY2023. In order to establish an environmentally safe, inexpensive CO_2 capture technology using a solid sorbent, we complete the detailed design during FY2022 and plan to finish the environmental impact assessment test by the end of FY2023.

(2) Moving bed system and demonstration test plant

As shown in **Fig. 4**, the moving bed system continuously recovers CO_2 by moving the solid sorbent itself to an absorption tower for absorbing CO_2, a desorption tower for desorbing CO_2 with steam, and a sorbent dryer for drying the moisture absorbed from the steam, and then circulating the solid sorbent from the sorbent dryer back to the absorption tower by a conveyor. This method enables the desorption tower to continuously desorb CO_2, thus reducing the separation energy compared to the fixed bed system. We have constructed a bench-scale test plant at our Akashi Works with a recovery rate of 5 t-CO_2/day and are developing it as a KCC for large-scale recovery.

Based on our achievements at this bench-scale plant, we are conducting a long-term continuous operation demonstration test of a pilot-scale moving bed plant with recovery of 40 t-CO_2/day at Kansai Electric Power Company's Maizuru Power Station in collaboration with the Research Institute of Innovative Technology for the Earth (RITE). This is being done under a project of the New Energy and Industrial Technology Development Organization (NEDO) entitled "Commercialization of Advanced Solid Absorbents for CO_2 Capture, in R&D of CO_2 Separation/Capture Technologies, under Development of Technologies for Carbon Recycling and Next-Generation Thermal Power Generation." We are responsible for the design, manufacture, installation, and commissioning of the pilot-scale moving bed plant. Construction work started in 2021, and the plant was completed in FY2022 (**Fig. 5**).

Using an amine-impregnated solid sorbent for coal flue gas newly developed by RITE, we successfully demonstrated CO_2 recovery by FY2022. Next, maximum recovery tests, parameter change tests, and continuous operation tests will be conducted using this pilot plant by FY2024 in order to establish an operation method for the KCC process as well as to develop and verify the continuous operation and control response capability to be marketed and applied commercially.

After completing the demonstration test, we plan to develop a commercial plant capable of recovering up to

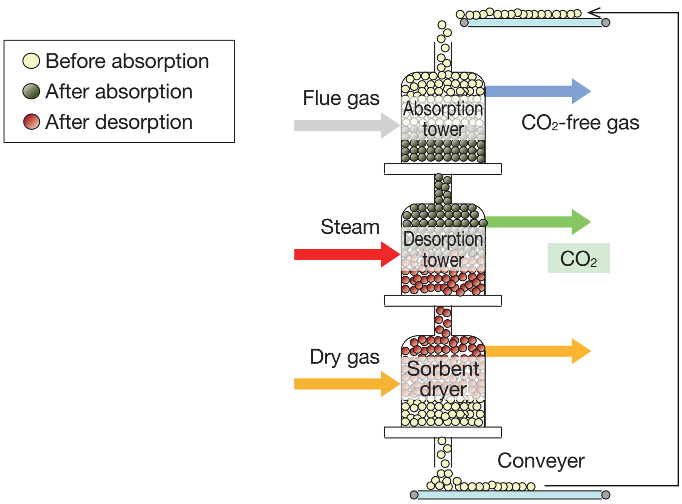

Fig. 4 Moving bed solid sorbent process

Fig. 5 Pilot-scale moving bed solid sorbent plant

Fig. 6 Demonstration plant for DAC

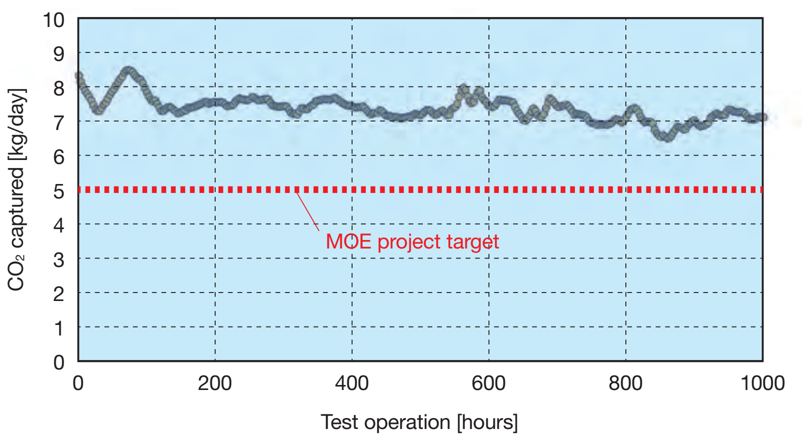

Fig. 7 DAC CO_2 capture test

several thousand tons of CO_2/day and start commercial application to small- and medium-sized emission sources as well as thermal power plants.

(3) DAC development

Our amine-impregnated solid sorbent development stemmed from DAC for submarines and can be applied to direct capture from ambient air, which has a lower CO_2 concentration than flue gas. Under the Ministry of the Environment, Government of Japan (MOE) project entitled "Modeling of Carbon Circulation Society with Direct Air Capture and CO_2 Utilization," we established a small demonstration plant (**Fig. 6**) with a capture capacity of 5 kg-CO_2/day (about 2 t-CO_2/year) at our Akashi Works and completed a demonstration test by FY2022.

In this demonstration test, we used our newly developed solid sorbent. During 1,000 hours of continuous operation, the amount of CO_2 captured was confirmed to be 6.5 to 8.5 kg-CO_2/day, which is higher than the project target of 5 kg-CO_2/day, as shown in **Fig. 7**. The purity of the recovered CO_2 was 99% or more. In addition, CO_2 recovery tests using air that simulated seasonal and weather changes were conducted to evaluate seasonal dependence, and data for commercial deployment has already been obtained.

Conclusion

We are developing our KCC energy-saving CO_2 capture system through demonstration tests in order to realize commercial-scale plants. With our innovative low-carbon solid sorbent technology, we intend to further advance our development to achieve global decarbonization.

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New Ash Handling System That Makes It Possible to Recover Energy from Combustion Ash and Convert It into Valuable Resources

The Japanese government announced its policy for achieving carbon neutrality by 2050. We believe that we could contribute to society by reducing environmental impact, including lowering CO_2 emissions and recycling energy with technologies to make effective use of ash generated in power plants using coal and biomass as fuels. We established recycling technologies to make effective use of bottom ash, which is combustion ash discharged underneath the boiler, and fly ash, which is collected from combustion gases, and conducted bench testing and demonstration testing to verify their effectiveness.

Introduction

In Japan, efforts are underway in various industries to achieve carbon neutrality by 2050. These efforts include approaches to energy recovery and CO_2 reduction.

1 Background

In the combustion ash of coal or biomass fuels, there is "unburned carbon" that ideally should have been combusted in the boiler. A high amount of unburned carbon in ash can lead to energy loss. Additionally, an increased quantity of ash that becomes industrial waste is directly associated with increased environmental loads and rising costs for end-users in ash disposal. Moreover, from the perspective of utilizing ash effectively, the amount of unburned carbon in ash must be decreased.

Combustion ash consists of bottom ash, which is discharged underneath the boiler after combustion in the boiler, and fly ash, which is contained in the boiler combustion gas and collected by the dust collector from combustion gas before discharging the gas to the atmosphere.

Regarding bottom ash, more than 60% of coal-fired power plants currently in operation in Japan have been running for more than 20 years since commissioning. Many are using wet processing methods, and they have aged significantly. Because of this, it is expected that there will be increased demand for retrofitting to dry processing facilities, which enable energy recovery and reduce environmental impact.

Regarding fly ash, a significant portion of the domestically generated quantity is recycled as a substitute for clay as a cement material, but CO_2 is emitted during the cement manufacturing process. However, cement blended with high-quality ash, known as fly ash cement, which meets the specified criteria for unburned carbon content in ash, has the potential to reduce CO_2 emissions during production compared to manufacturing an equivalent amount of regular cement. Therefore, given the social backdrop of the desirability of a recycling-based society, demand for fly ash cement is expected to increase.

In response to this situation, we have established recycling technologies for the combustion ash of coal and biomass fuels, which can potentially reduce environmental impact and enable energy recovery.

2 Overview of the ash handling system

Typical handling systems for bottom ash and fly ash are illustrated in **Figs. 1** and **2**, respectively. Bottom ash is conveyed while being air-cooled through a dry bottom ash conveyor and a bottom ash cooling conveyor. After passing through a crusher, it is temporarily stored in a tank and then transported by truck or sent to downstream

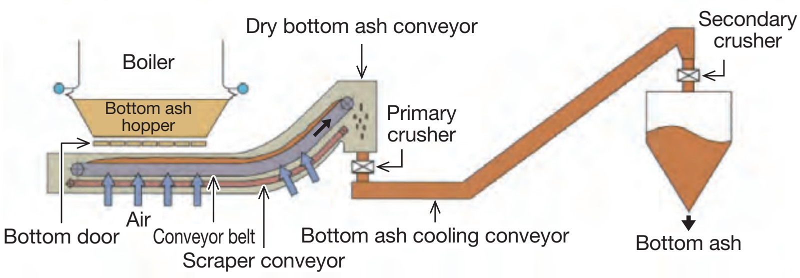

Fig. 1 Bottom ash handling system (dry)

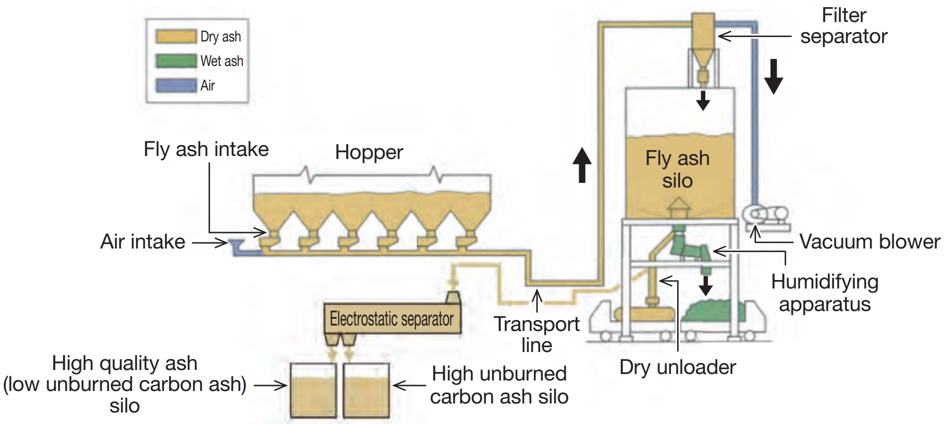

Fig. 2 Fly ash handling system (vacuum conveyance)

facilities by a pneumatic conveying system. In contrast, fly ash is vacuum-conveyed by a blower, collected through a filter separator, and then stored in a fly ash silo. There are two methods for discharging ash from the silo to trucks: when discharging as dry ash, dry unloader is used, and when discharging as wet ash, a humidifying apparatus is used.

3 New dry bottom ash handling system "KACE" (Kawasaki Ash Cooling / Conveying Extractor)

(1) Development background

A dry bottom ash handling system discharges bottom ash as dry ash; therefore, it has advantages such as increased opportunities for effective utilization and the potential for reducing utility usage in facilities. On the other hand, when low grade coal such as sub-bituminous coal is used, problems may occur in downstream transport of ash with the method currently in use if excessively large lumps of bottom ash are formed within the boiler. To address this issue, we have developed the new bottom ash handling system "KACE" (Kawasaki Ash Cooling/ Conveying Extractor), which can mitigate problems in downstream equipment by discharging large lumps of bottom ash in an intact state.

(2) Equipment concept

(i) Discharge of big lumps from the system

Fig. 3 shows an overview of "KACE". Bottom ash generated in the boiler passes through the bottom ash hopper located at the bottom of the boiler, and it is next separated into big lumps and fine particles in the grizzly[1),2)]. Big lumps are manually deposited into the big lump collection box by manually opening the big lump gate. Subsequently, they are manually transported to ash disposal sites or other designated locations. Small particles are transported to the downstream facilities by the dry bottom ash conveyor. By enabling the discharge of big lumps from the system, the following can be expected:

① prevention of dry bottom ash conveyor shutdowns caused by clogging due to big lumps; and
② reduced installation costs attributable to the reduction in size of the under- boiler conveyor.

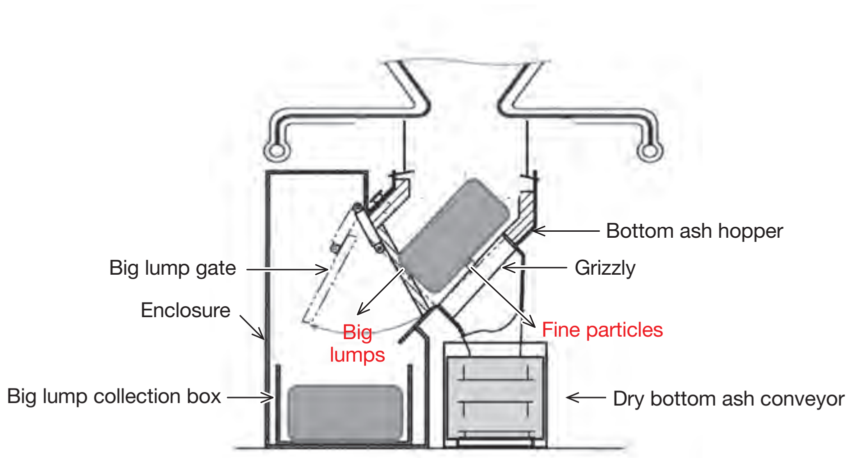

Fig. 3 Schematic of KACE

(ii) Energy recovery from unburned carbon (unburned biomass)

Compared to coal firing boilers, boilers for coal and biomass mixed firing and dedicated biomass firing boilers have a significantly higher proportion of unburned carbon in their bottom ash. For example, while coal-firing boilers may have around 5%, biomass co-firing boilers can have proportions ranging from 40% to 50%. Using a wet system results in the disposal of a large amount of unburned carbon, preventing energy recovery. Additionally, increasing the biomass co-firing rate for the purpose of reducing CO_2 emissions leads to a corresponding increase in unburned carbon—in other words, an increase in the amount of industrial waste.

Therefore, by changing the bottom ash conveying method from wet to dry, the following become possible from the perspective of energy recovery.

① Heat recovery through continued combustion brought about under the boiler

Cooling of bottom ash on the conveyor utilizes the atmosphere drawn through the air intake using the negative pressure of the boiler. This allows the bottom ash to continue the combustion reaction even after falling under the boiler or the bottom ash conveyor, and the heat energy generated during this process is recovered by the boiler through the inflow of air.

② Recovery of unburned carbon (mainly from unburned biomass) through reintroduction of ash into the boiler

After finely grinding the bottom ash carried by the conveyor, it is reintroduced into the boiler by air transport. This process facilitates complete combustion of the remaining unburned carbon (mainly from unburned biomass) in the bottom ash inside the boiler. This is referred to as "MAR (Magaldi Ash Recycling)", a technology held by Magaldi Power S.p.A., an Italian company with which we have a technological partnership.

(3) Bench testing

We fabricated bench testing equipment and confirmed that the equipment operates smoothly under thermal load and that there are no issues with the separation function of the grizzly.

Based on the findings from the bench test, we incorporated the following aspects into the design of the demonstration unit.

① Enhanced sealing performance between the big lump gate and hopper

To prevent ash from spouting through the gap between the big lump gate and the hopper while the boiler pressure is positive, we modified the gate shape from the one used in the bench test in order to improve its sealing performance.

② Measure to resolve biting with the grizzly

Mid-sized lumps with diameters of approximately φ200 to be separated by the grizzly may become bitten with the grizzly or the shielding (a block that protects the rotary shaft from shocks when big lumps fall), and such biting may not resolve themselves. Therefore, to facilitate ash discharge, multiple protrusions were installed on the shaft to form a shape that resolves biting during shaft rotation. Additionally, the shape of the shielding was modified to facilitate ash discharge.

(4) Demonstration test

We removed the wet conveyor installed under the operating boiler and installed demonstration testing equipment as shown in **Fig. 4**. We then verified the following aspects.

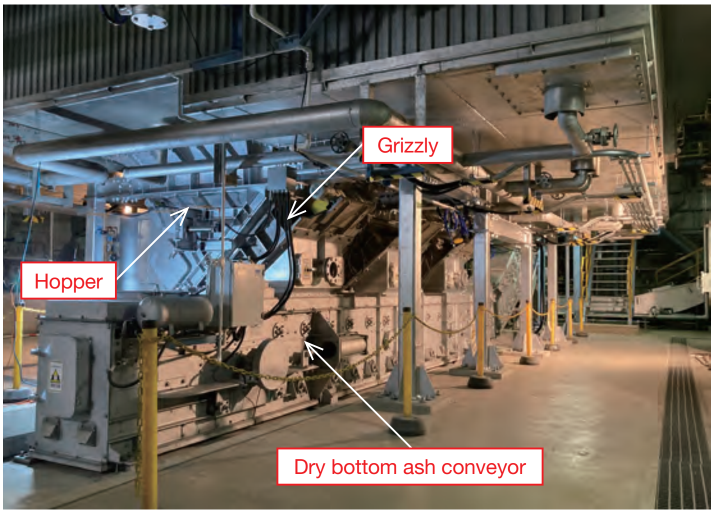

Fig.4 Exterior of demonstration testing equipment (front of boiler side)

(i) Function verification

- Separation function in the grizzly
  While there were instances in which small- to medium-sized lumps accumulated in the hopper chute incline, we confirmed that the majority are discharged after a certain period, and separation was performed without issue.
- Discharge from the big lump gate
  We confirmed that lumps that accumulated in the hopper were discharged without issue.
- Method for dealing with blockages occurring in the grizzly section
  We confirmed that blockages caused by clinker in the discharge outlet can be resolved by pushing from the chute inspection opening.

(ii) Evaluation by measurement at different points

- Atmospheric temperature in the bottom ash hopper
  We confirmed that it was between approximately 250 and 350°C, which is on the safer side compared to a strength evaluation condition of 450°C or lower.
- Ash temperature inside the dry bottom ash conveyor
  The high-temperature (red-hot) bottom ash at 600-800°C at the inlet showed a temperature decrease of 100-300°C while being transported on the conveyor incline.
  Normally, the temperature of falling ash is 100 to 200°C at the inlet, while it was 100°C or lower at the discharge outlet.
- Measurement of temperature at various sections (hopper, grizzly, gate, etc.)
  We confirmed that the temperatures were on the safer side compared to the temperature distribution obtained by analysis.

(iii) Consideration of energy recovery

An increase in combustion efficiency was observed after installation of the demonstration testing equipment, compared to that during wet conveyor operation prior to installation (prior to installation: approx. 99.3%; after installation: approx. 99.6%). This is believed to be a result of conversion to a dry system, in which the unburned carbon content in the bottom ash continues combustion reactions under the boiler. Additionally, eliminating the need for seal water under the boiler due to the transition to a dry system resulted in the absence of moisture (evaporated seal water) entering the boiler. This absence of moisture is believed to have contributed to the increase in overall boiler temperature, promoting combustion not only of the bottom ash but also of the unburned carbon in the fly ash.

4 System for removing unburned components from fly ash using electrostatic separate technology

As a method of producing high-quality ash, for which demand is expected to increase, we possess electrostatic separate technology. We have been developing this technology since around 2003[3),4)] by confronting challenges such as downsizing the equipment and improving the recovery rate. Most recently, we have been aiming to realize methods that enable us to increase the handling amount.

(1) Separation of unburned carbon and valuable recycling of ash

To turn ash into high-quality ash (valuables), it is necessary to reduce the amount of unburned carbon in the ash to below the specified level. As a method to do so, we have developed the system shown in **Fig. 5**, which uses electrostatic separate technology to separate unburned carbon from ash.

When ash raw powder is introduced to a porous plate and a mesh-like plate is placed above it, applying a voltage between the two results in neutral ash remaining on the porous plate, which serves as a positive electrode, while charged unburned carbon is attracted to the mesh-like plate, which serves as a negative electrode. The movement of unburned carbon is assisted by flowing fluidizing air from the bottom of the porous plate. The separation of unburned carbon from ash achieved by this technology enables conversion of ash into valuable resources, whereas conventionally disposal costs have been incurred.

(2) Reduction in CO_2 emissions during cement manufacturing

Japan's domestic CO_2 emissions from cement manufacturing in fiscal year 2019 totaled 41.47 million tons, accounting for approximately 3.7% of the total direct emissions of 1.10794 billion tons. As mentioned earlier, widespread adoption of fly ash cement could contribute to increased demand for high-quality ash domestically, leading to a reduction in CO_2 emissions. Compared to conventional cement manufacturing, it is possible to reduce CO_2 emissions by approximately 20%.

(3) Bench testing

Fig. 6 is a schematic diagram of the bench testing equipment. In the process of introducing ash onto the porous plate and guiding it to the discharge outlet through the vibrator, a voltage is applied between the high

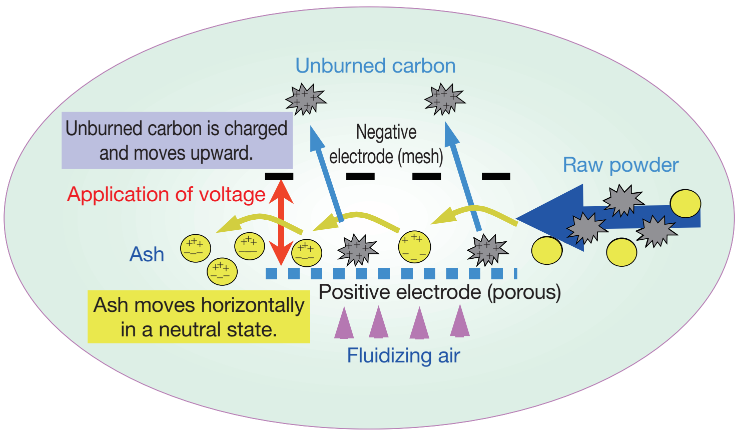

Fig. 5 Principle and concept of electrostatic separate technology

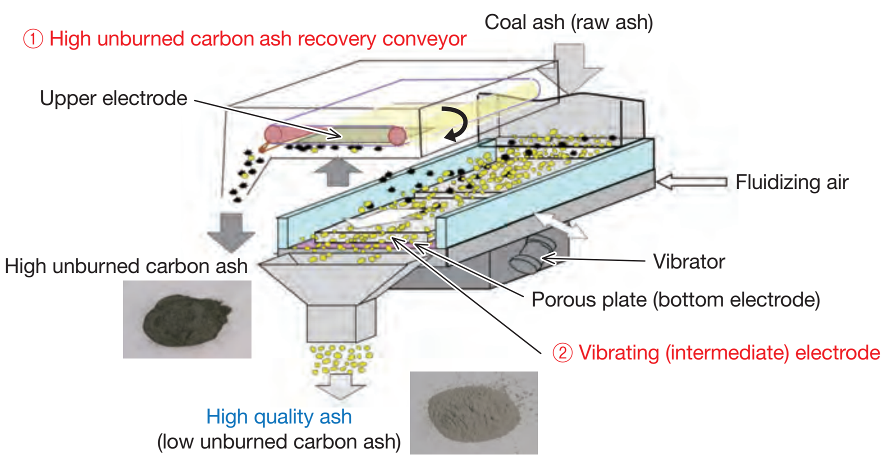

Fig. 6 Bench testing equipment

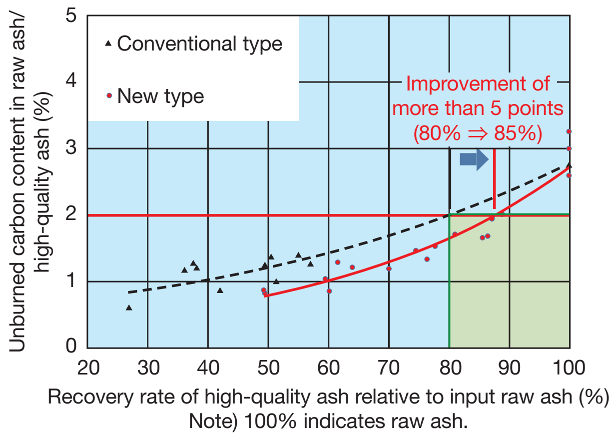

Fig. 7 Bench testing results

unburned carbon recovery conveyor, which serves as an upper electrode, and the porous plate. Fluidizing air is simultaneously introduced from the bottom of the porous plate, allowing the unburned carbon to be collected and conveyed to the recovery conveyor.

The conventional type suctions unburned carbon that has moved to the upper electrode while vibrating the entire apparatus, resulting in an enlarged device. However, in our bench testing equipment, vibration is applied only to the intermediate electrode, and unburned carbon is not suctioned but instead adhered to the belt. This design enables device downsizing and improved recovery efficiency.

Using this system, the unburned carbon separation performance was checked at two power plants in operation. The results of the bench test are shown in **Fig. 7**. In this test, the target performance items were the percentage of unburned carbon in high-quality ash and the recovery rate of high-quality ash relative to the input raw ash. The former was set to the general requirement in cement manufacturing of 2% or less, while the latter was set to 80%, which is the performance of the previous machine, or more. The unburned carbon amount was determined from the mass ratio before and after heating the recovered high-quality ash. In comparing the conventional type with our bench testing equipment, both are capable of reliably separating ash with a varying amount of unburned carbon content. However, our bench testing equipment showed a significant improvement in the recovery rate, exceeding 5 percentage points, indicating high separation performance.

Conclusion

For "KACE", the new dry bottom ash handling system, demonstration testing is complete, and we are now conducting sales activities to obtain commercial orders. As for the system for removing unburned carbon from fly ash using electrostatic separate technology, we have confirmed its high separation performance through bench testing. We are currently planning how to proceed to the stage of demonstration testing. We aim to contribute to achieving carbon neutrality by applying these technologies to recover energy and effectively utilize ash.

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Labor-Saving Technologies for Municipal Waste Treatment Facilities and Recycling Facilities

Because of the declining workforce, municipal waste treatment facilities and recycling facilities are expected to face greater difficulty in securing a sufficient number of operators, and it is increasingly important to develop labor-saving technologies for economical and efficient facility operation.

In response to this situation, we have developed systems for reducing the burden of operators by using ICT (Information Communication Technology) and robot technology, including KEEPER, a system for remotely monitoring and supporting the operation of municipal waste treatment facilities, and K-Repros, a support system for hand-sorting recyclable waste in recycling facilities.

Introduction

Due to changes in Japan's social environment in recent years, such as the decreasing workforce and the prevalence of large-scale disasters and infectious diseases, it is predicted that securing operators will become increasingly challenging in the future. Society has a growing need for more efficient operations to be performed by fewer operators, and municipal waste treatment and recycling facilities are no exception.

1 Background

Municipal waste treatment and recycling facilities are crucial social infrastructure facilities that support the foundation of daily life; they must be operated safely and reliably. To ensure stable facility operations, the presence of operators who manage and assist the operational status is essential. To operate facilities efficiently in the face of a decreasing workforce, it is necessary to develop a driving system that can ensure stable operation independently of an operator's experience.

At present, we are advancing the development of labor-saving technologies such as a remote monitoring and operation support system as well as a support system for hand-sorting recyclable waste for municipal waste treatment facilities and recycling facilities. These technologies are designed to augment human perception, decision-making, and tasks performed in the course of operating such facilities. We are working on technological development aimed at systematizing the expertise of operators to reduce their burdens, thus enabling resources to be shifted to tasks that require more human involvement.

2 Remote monitoring and operation support system for municipal waste treatment facilities

Waste treatment facilities reduce and render harmless general combustible waste, including household waste, through incineration treatment. Collected waste is placed in a waste treatment facility's waste pit, where it efficiently undergoes complete combustion in an incinerator to reduce its volume. The incineration exhaust gases are neutralized in an exhaust gas treatment system and then released through the chimney. Additionally, the heat energy generated during incineration is utilized for power generation or heat supply.

(1) Challenges to achieving labor-saving operation at municipal waste treatment facilities

Waste treatment facilities are controlled using a Distributed Control System (DCS), and incinerator operation is automated through Automatic Combustion Control (ACC). Due to the heterogeneous nature of the waste being processed, manual operation may be necessary to assist in achieving stable combustion when there are significant fluctuations in the characteristics (quality or heat generation amount) of the waste. Therefore, to ensure stable operation of waste treatment facilities, experienced operators who can monitor the incinerator's combustion status and assist in automatic combustion control are indispensable.

To achieve labor-saving operation at waste treatment facilities, challenges include ① remote monitoring support for incinerator supervision and operation by on-site operators, ② stabilization of the characteristics of the waste to be fed into the incinerator, and ③ correction of ACC according to fluctuations in combustion conditions.

(2) Labor-saving technologies for municipal waste treatment facilities

① Remote monitoring and operation support system KEEPER

In FY2016, we introduced KEEPER (Kawasaki Expert Environmental Plant Engineered Remote support system), a system for remotely monitoring the operation of municipal waste treatment facilities. In this system, the environmental remote monitoring room within our Kobe Works is connected to the operation monitoring systems of various facilities throughout Japan via an IP-VPN (Internet Protocol-Virtual Private Network, a virtual dedicated line) to enable centralized monitoring to be performed remotely. Initially, the system targeted four facilities, but with the order for the DBO (Design-Build-Operate) project, the number of targeted facilities has been increased to 12 as of March 2023.

This system is built on top of NTT PC Communication's Master's ONE IP-VPN platform, ensuring security. Efforts are made continuously to maintain and enhance high-security measures on the hardware side, including the network. Moreover, as a countermeasure against attacks on security by surveillance personnel or employees, regardless of whether or not they are malicious, Cyber Security Management System (CSMS) certification was obtained in October 2020 (as of March 2023, it has been obtained by three companies), as shown in **Figure 1**, and is now being implemented.

KEEPER utilizes the extensive operating experience of our veteran operators to provide support services for monitoring and checking/diagnosis of operating conditions at each facility (on-site) via 24-hour surveillance. Additionally, it also functions as a data center for collecting, storing, and analyzing operational data from each facility, and operates an AI-powered operation support system. This system replicates the manual operations performed during incinerator operation using AI with the aim of stabilizing combustion and reducing operators' workloads; it recommends the optimal manual operations to operators. As shown in **Figure 2**, the AI associates and learns from facility operation data such as process data,

Fig. 1 CSMS certification logo and remote monitoring room

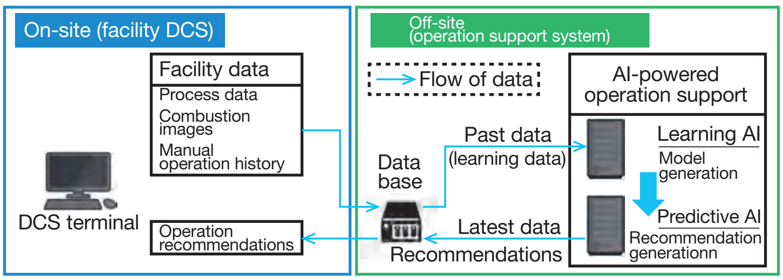


Fig. 2 Overview of operation support system using AI

combustion images, and the history of manual operations that have been performed. When the AI determines that the current operational situation is similar to past instances in which manual operations were performed, it automatically outputs recommendations for such operations[1].

The learning AI accesses the database of the remote monitoring system, in which each facility's operational data is stored, to generate computational models by learning the accumulated data. The predictive AI generates operation recommendations based on these computational models and the latest data. The learning AI can generate computational models as needed, which enables the system to perform additional learning whenever operational data from each facility is added.

② Stabilization of waste incineration using an optimal operation system for waste cranes

The fundamental point to achieve stable combustion in an incinerator is to stabilize the waste quality (heat generation amount) as much as possible, and a major factor causing significant variations in waste quality is moisture. Conventionally, it has not been possible to quantitatively understand waste quality in a waste pit. Therefore, it was necessary for operators to perform manual mixing of the waste pit by visual inspection (such as the color of the waste, the weight when grabbed by a waste crane, etc.) As a system for optimizing waste crane operations, we have developed an automatic operation technology that combines quantitative measurement of moisture in the waste with the optimal mixing method of the waste pit by the waste crane.

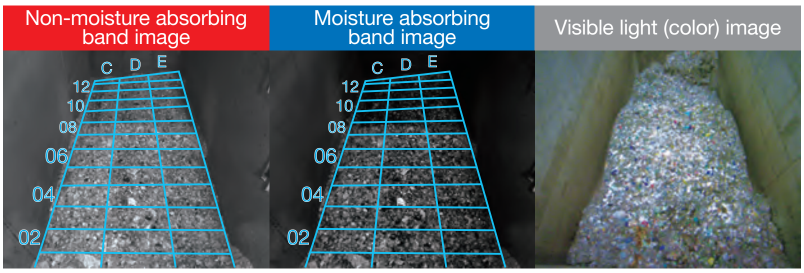
Using a moisture camera, we quantify the moisture index in the waste by capturing images with a near-infrared camera; we then compare the difference in brightness between the moisture absorption band and the non-moisture absorption band, where the impact of water is minimal. Utilizing the distribution data of moisture indices across the entire pit, as shown in **Fig. 3**, the optimal mixing to homogenize the distribution of moisture indices in the waste pit is performed automatically and efficiently by the waste crane.

③ Automatic correction of ACC by the AI-assisted operation support system

The operation recommendations sent from the operation support system are used in both guidance mode, in which the operation terminal and operation direction are displayed qualitatively in the facility's DCS, and AI correction mode, in which automatic correction is applied to the ACC, as shown in **Fig. 4**. The range of manipulated variables corrected by the AI can be set for each operation terminal on the facility DCS (on-site). By using ACC to integrate the operation recommendations reproducing the combustion monitoring and manual operations of operators based on past operational data, the scope of automatic operation can be expanded, reducing the burden of manual operations imposed on operators.

(3) Demonstration experiment

From January to March 2021, we experimentally conducted remote operation by taking over operations in the environmental remote monitoring room in order to demonstrate the system. When performing remote operation using KEEPER, the environmental remote monitoring room can receive the same information as the central control room (operation control screens, ITV images). However, it cannot obtain the operating status of each piece of equipment in the machine room. Therefore,



	Moisture index value (* moisture index value by address)													
E	39. 3	39. 6	44. 5	43. 2	43. 3	46. 5	45. 2	46. 8	47. 0	45. 6	39. 1	40. 7	36. 6	41. 3
D	39. 6	43. 4	47. 3	45. 6	47. 1	45. 8	42. 4	45. 6	45. 0	41. 5	38. 4	35. 8	40. 9	41. 5
C	44. 1	46. 0	46. 7	44. 5	43. 6	40. 0	40. 5	45. 3	45. 1	43. 9	40. 1	35. 5	31. 6	38. 1
Address	01	02	03	04	05	06	07	08	09	10	11	12	13	14

Fig. 3 Moisture content camera image and moisture content index map

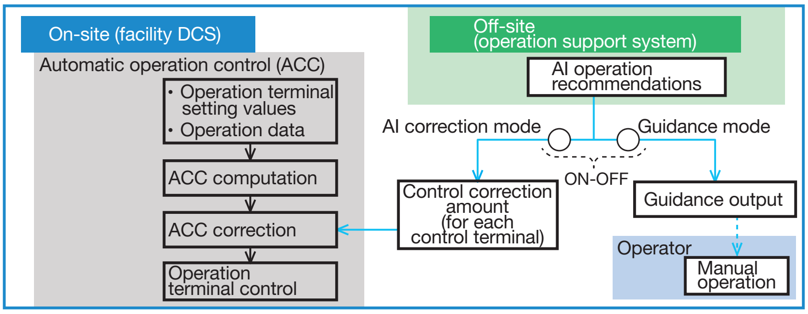


Fig. 4 System using operation recommendations

to address this limitation, remote operation was performed in collaboration with the actual site.

At the Chita Southern Broad Area Environment Center, which was completed in March 2022, an automatic ACC correction system using the waste crane optimal operation system and AI-powered operation support system has been adopted. The demonstration experiment for this system verified stable operation that eliminates the need for manual operation for two weeks. In addition, backup operation by operators in the environmental remote monitoring room via 24-hour monitoring is performed in combination, thus realizing labor-saving operation by utilizing labor-saving technologies.

3 AI-powered support system for hand-sorting recyclable waste K-Repros

To recycle glass bottles, cans, plastic bottles, and the like, recycling facilities perform sorting treatment as well as compaction and packaging. Among these items, glass bottles must be sorted by color for recycling. Generally, they are divided into the three categories of brown bottles, clear bottles, and bottles of other colors.

(1) Issues for labor-saving in the bottle sorting process

In the glass bottle sorting process, recovered materials vary in size from small bottles, such as energy drink bottles, to heavy bottles, such as 1.8 L bottles, and the sorting targets consist of numerous combinations of colors and sizes. Additionally, materials collected as glass bottles may include foreign objects such as caps that cannot be recycled into glass bottles, necessitating a process for removing such foreign objects during the sorting process. Given such circumstances, hand-sorting by multiple workers has been widely adopted to improve sorting accuracy.

K-Repros, an AI-powered support system for hand-sorting recyclable waste, was developed with the aim of assisting in color sorting work in collaboration with the manual sorting work performed by operators, as depicted in **Fig. 5**. The challenges to developing this system were ① facilitation of coexistence and collaboration between robots and humans, ② the glass bottle identification technology, and ③ development of a hand that can grip a bottle.

(2) AI-powered support system for hand-sorting recyclable waste K-Repros

Fig. 6 shows a system overview of K-Repros. This system is composed of a recognition unit that automatically detects and identifies the sorting target bottles based on image data and a gripping unit that picks up bottles based on signals sent from the recognition unit. The gripping unit is composed of a robot and a hand attached to the end of the robot arm. To overcome the

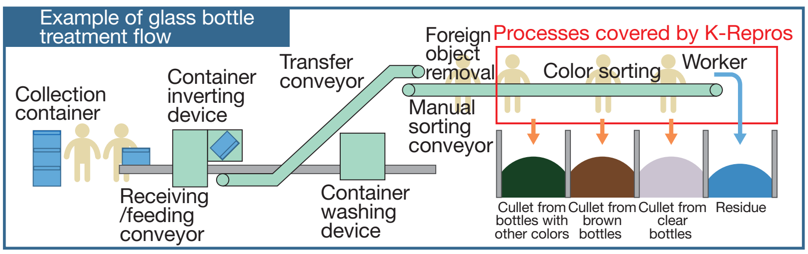


Fig. 5 Processes covered by K-Repros

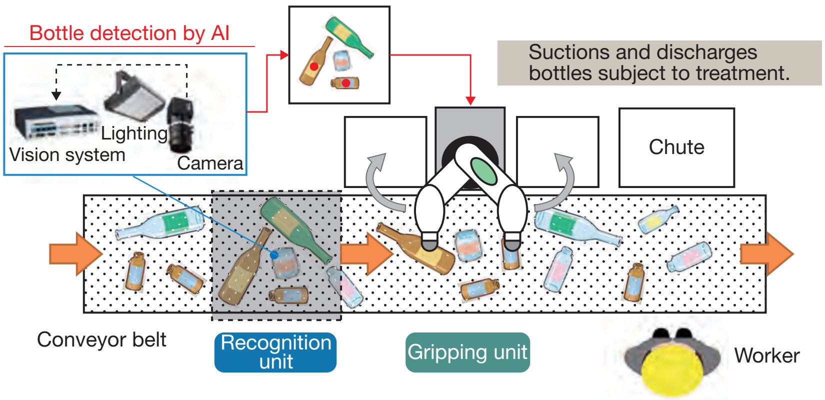


Fig. 6 Overview of K-Repros system

Fig. 7 Example of detection using AI

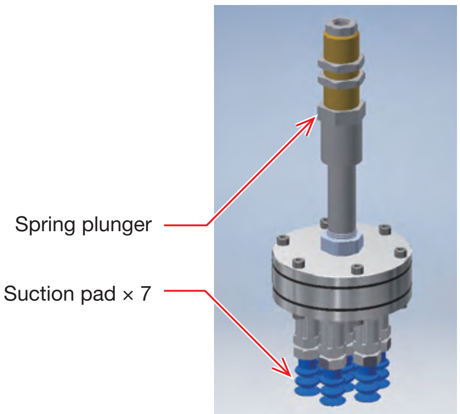


Fig. 8 Construction of hand

Fig. 9 Demonstration experiment

Table 1 Verification results of accuracy of identification using AI

Glass bottle type	Precision ((B-D)/B)	Detection rate (B/A)	Number of treatment targets (A)	Number of detected targets (B)	Number of undetected targets (C)	Number of false detections (D)
Brown	100%	97.4%	534	520	14	0
Clear	100%	97.3%	515	501	14	0
Other colors	100%	96.6%	298	288	10	0
Average (total)	100%	97.2%	(1347)	(1309)	(38)	(0)

aforementioned challenges, the following three aspects have been developed and implemented.

① Coexistence and collaboration achieved by duAro2

The gripping unit adopts our cooperative robot duAro2, which enables workers and robots to work together in the same space. duAro2 can coexist and collaborate with humans due to its various functions that ensure safety, including a collision detection function and the use of parts made of soft materials for the robot's surface. In addition, it does not require isolation fences and is sufficiently compact to be installed in a space for a single person. Moreover, it can easily be moved by a dolly with casters using the built-in controller.

② Bottle identification by AI

The recognition unit adopts our proprietary AI that specializes in identifying bottles. The unit can extract targets from input image data by deep learning. As shown in **Fig. 7**, the AI automatically identifies the bottle color from features such as the color and shape based on image data captured by the camara and then determines the gripping point for the target.

③ Bottle gripping by a vacuum suction hand

The hand of duAro2 adopts the vacuum suction system shown in **Fig. 8**. Differences in the suction surface height due to differences in bottle size are absorbed by the spring plunger, and bottles are suctioned by the suction pads placed at the end of the hand. Compared to the gripper system that sandwiches the target by opening and closing multiple claws, this system has superior gripping speed and is capable of gripping bottles regardless of their orientations, shapes, and sizes. It can grip the target object alone even in a situation in which the treatment targets are concentrated, thus ensuring highly reliable gripping.

(3) Demonstration experiment

To verify the identification accuracy and processing capacity of the AI, this system was installed on the manual sorting conveyor of a recycling facility where a manual bottle sorting process is actually performed, as shown in **Fig. 9**. and an experimental demonstration was conducted. In manual glass bottle sorting at recycling facilities, high accuracy is often required to achieve purity (the mixing ratio of bottles with different colors) after color selection; therefore, in constructing an AI model, emphasis was placed on minimizing the number of false detections, such as color mismatches, rather than maximizing the bottle detection rate.

The verification results of identification accuracy using AI are listed in **Table 1**. The precision, which indicates the extent of mixing other colored bottles into the target colored bottles, was 100% for all types. A precision of 100% indicates a state in which there are no color mismatches, and all instances have been correctly sorted by the relevant target color. In addition, the detection rate, which indicates the percentage at which the AI identified bottles, averaged 97.2%. This demonstrates high accuracy in color recognition while achieving satisfactory performance with respect to the bottle detection rate. The ratio of the processing capacity of one robot to the workload of one worker is maintained at around 50%, confirming the anticipated result for the capabilities of this system, which is designed to enable coexistence and collaboration between humans and robots through the deployment of a cooperative robot.

Conclusion

To achieve stable operation of facilities over an extended period, it is essential to build an operation system that ensures stable operation without relying exclusively on the experience of veteran operators. Furthermore, it is predicted that it will become increasingly challenging to secure operators; therefore, labor-saving technologies will become more and more important in municipal waste treatment facilities and recycling facilities. We will continue to work to develop these technologies while considering the progress in Information and Communication Technology (ICT) and other relevant factors.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Development of Advanced Safety Berthing/Unberthing Assistance System Aimed at Achieving Zero Vessel Accidents in Ports

In ports, which are congested with ships and require sensitive vessel maneuvering, many accidents are caused by human factors, and a higher level of safety is required. Taking advantage of our product technologies for marine propulsion systems and general marine machinery, we are working with Kawasaki Kisen Kaisha, Ltd. and Kawasaki Kinkai Kisen Kaisha, Ltd. to develop the world's first advanced Safety Berthing/Unberthing Assistance System that supports maneuvering in port, berthing/unberthing, mooring operations, and mooring management in an integrated way. We are conducting research and development by using Kawasaki Kinkai Kisen coastal vessels in actual service conditions, aiming for social implementation by 2025.

Introduction

In recent years, expectations have been increasing for the practical application of autonomous navigation technology for ships; this has been driven by aims such as the further enhancement of maritime safety, improved onboard working environments, and increased industrial competitiveness and productivity. To move toward social implementation of autonomous navigation technology, various approaches are being implemented across diverse sectors in Japan as well; for example, in 2018, the Ministry of Land, Infrastructure, Transport, and Tourism formulated the "Roadmap for the Practical Application of Autonomous Ships." In addition, in 2020, Class NK (the ship classification society) published the "Guidelines for Automated/Autonomous Operation of Ships—Design, Development, Installation and Operation of Automated Operation Systems/Remote Operation Systems."

Moreover, in the International Maritime Organization (IMO), the implementation of the MASS (Maritime Autonomous Surface Ships) Code, a framework of international rules, continues to be studied; the Code is planned to come into force in 2028.

1 Background

Despite advancements in navigational instruments and the development of IoT (Internet of Things) technologies, the number of maritime accidents has not decreased. For coastal vessels in particular, more than half of accidents occur in coastal areas, including in port facilities. To address this challenge, there is a need to improve safety during ship entry and exit.

Therefore, with the aim of achieving zero accidents during maneuvering within ports, Kawasaki Kisen Kaisha, Ltd. and Kawasaki Kinkai Kisen Kaisha, Ltd. are jointly working with our company on technological research and development concerning the advanced Safety Berthing/Unberthing Assistance System. This is the world's first system to support maneuvering in port, berthing/unberthing, mooring operations, and mooring management in an integrated way. As its primary feature, the system realizes comprehensive support from vessel entry to mooring operations and mooring management during berthing by means of coordinated control between the propeller and mooring-winch.

2 The aim of the three companies' joint development of the advanced Safety Berthing/Unberthing Assistance System

At present, berthing and unberthing operations in ports are carried out by crews who are well-versed in vessel maneuvering techniques and who have a deep understanding of the characteristics of ship-specific maneuvering and mooring equipment features. However, with the increasing size of vessels leading to advanced navigation requirements and the shortage of maritime personnel, which has become a social issue, there is growing demand to further enhance safety management in ship navigation and mooring operations. It is expected that this system will assist in safe berthing and unberthing maneuvers using cutting-edge technologies such as AI, thereby leading to skill simplification and helping to resolve challenges in berthing and unberthing operations. In the research and development toward practical application, we aim to integrate the abundant navigational expertise of our two collaborative development partners with Kawasaki's system integration technologies for propulsion systems and mooring assistance technologies cultivated through our many years in the marine machinery business; this will enable us to address various challenges in berthing and unberthing maneuvers and to ensure a higher level of safety in mooring operations.

3 The technology developed to realize the safe berthing/unberthing assist system

(1) Maneuvering in-port

Maneuvering in ports is characterized by low ship speeds as illustrated in **Fig. 1**. It is challenging due to the influence of external disturbances, such as weather and sea conditions, including wind and tidal currents. Therefore, there is a need for operators to decide judiciously to ensure safe vessel maneuvering under such conditions.

Technologies developed to address this include "vessel maneuvering assistance information technology," which incorporates sensing technologies to accurately recognize a ship's own maneuvering and the surrounding conditions, and ship state prediction technologies, which utilize the vessel motion model. Such technologies have made it possible to obtain both accurate information about the relative relationships with other vessels and quay walls within the port and highly accurate information related to ship motion predictions, such as the future course, speed, and stopping position for the ship's commander, in addition to future hazard prediction information based on such information. This information is displayed on a Human-Machine Interface (HMI) device. These technologies thus realize vessel maneuvering assistance that enables even less-experienced operators to make appropriate decisions on navigation safety.

By leveraging environmental perception sensor technology, which enables recognition of surrounding conditions by combining signals from multiple sensors (sensor fusion), and rapidly processing a vast amount of sensor data, the following information can be acquired on the vessel in order to assist the vessel operator:

- Accurate information on the position, orientation, and movement speed of the vessel itself, other vessels, and obstacles such as floating buoys; and
- Accurate information on the relative relationships between the vessel and the quay walls.

Figure. 2 shows an example of sensor fusion recognizing the quay wall section from laser distance measurement and image information. Furthermore, by estimating the influence of disturbances such as weather and sea conditions not captured by sensors and calculating future movement predictions (**Fig. 3**) utilizing the vessel motion model, it becomes possible to provide the vessel

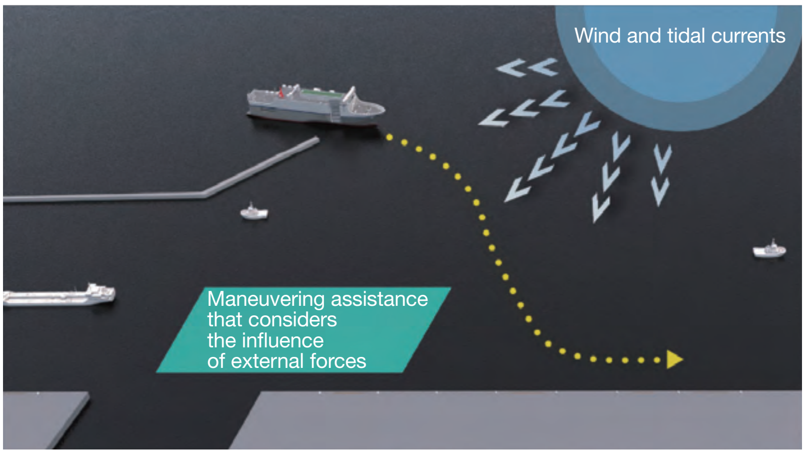

Fig. 1 Maneuvering in port and berthing/unberthing

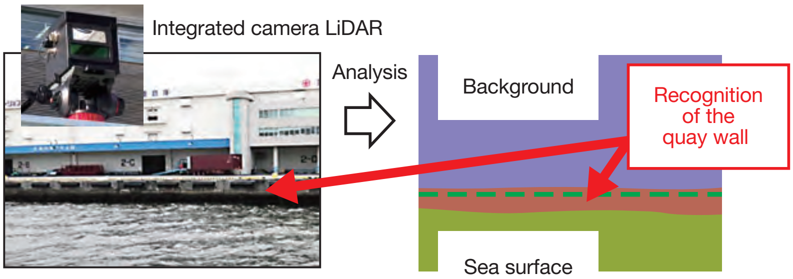

Fig. 2 Berth detection by LiDAR/camera fusion

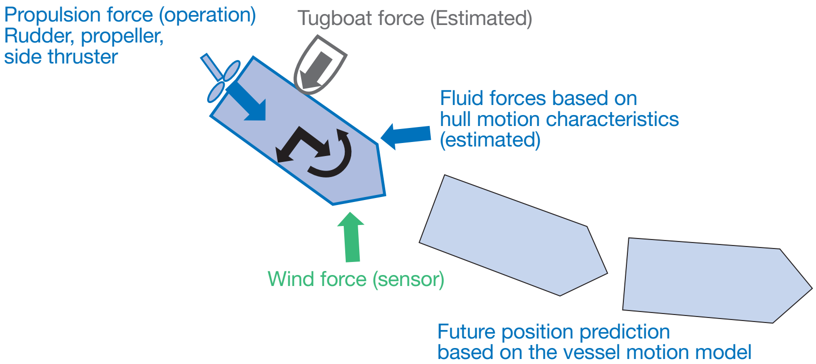

Fig. 3 Ship movement prediction that takes disturbance into consideration

operator with information such as the parallelism between the vessel and the quay wall during berthing, changes in the angular velocity, the approach speed to the quay wall, and the vessel's predicted future position.

(2) Berthing/unberthing operations

In berthing/unberthing operations close to the quay wall, vessel operators must simultaneously perform tasks such as appropriately reducing speed towards the target stopping position and maintaining both distance from and parallelism to the quay wall while considering the effects of disturbances, including weather and sea conditions. This is an extremely burdensome task for operators, so there is a need to reduce their workloads.

To address this need, the adoption of model predictive control utilizing vessel motion models enables prediction of the future vessel speed or attitude as well as calculation of the optimal thrust command; doing so provides optimal automatic control of the vessel speed and attitude, which are affected by constantly changing disturbance forces, such as weather and sea conditions. We have realized a vessel maneuvering assistance system that includes a function for automatically maintaining the ship's speed, thus compensating for external disturbances and ship attitude. This function reduces the workload imposed by vessel maneuvering operations, enabling operators to focus on making appropriate deceleration command decisions toward the target stopping position and sequential safety judgments for vessel maneuvering.

We manufacture and sell the KICS (Kawasaki Integrated Control System) collective control system, which can collectively control multiple types of propulsion machinery, including controllable pitch propellers, azimuth thrusters, side thrusters, and rudders. We have a wealth of experience in maneuvering various types of vessels, including ferries, supply boats, cable-laying ships, and fishing vessels[1), 2), 3)]. **Fig. 4** shows an example system configuration. Prediction of ship movements is enabled by a system configuration that combines navigation sensors—such as gyrocompasses, positioning systems, wind sensors, and log speed meters—with a control unit that incorporates a vessel motion model that represents the dynamic characteristics of the vessel. This system configuration allows the system to instantly calculate the blade angles, rotation speeds of multiple propellers, and rudder angle in response to disturbances such as wind and waves, thereby automatically optimizing the control.

(3) Mooring operations

In mooring, propeller operation at the bridge and

Fig. 4 Example of system construction of KICS-5000

mooring winch operation on the deck, as shown in **Fig. 5**, must be coordinated. In addition, there is a need to improve safety during vessel maneuvering.

The development of integrated coordination technology for propellers and mooring winches makes it possible to coordinate operations between the propellers and mooring winches from the remote bridge. In such coordinated operation, the mooring winch control system automatically controls the tension to generate the optimal tension while ensuring balance with the propeller. Additionally, this technology provides a function for using camera sensor technology to monitor whether there are any personnel near remotely operated mooring winches and mooring lines. The technology thus realizes mooring assistance that significantly reduces the risk of personal injury during mooring.

By applying the Dynamic Positioning System (DPS) technology included with KICS, which controls the heading, thrust commands for multiple propellers and mooring line tension commands for multiple mooring winches are optimally allocated to generate the desired resultant force that is balanced as the entire ship. **Figure 6** shows the control block diagram for KICS. This technology enables the position and attitude of the vessel performing berthing and mooring operations to be easily controlled, thereby realizing safe berthing and mooring at the specified position on the quay wall.

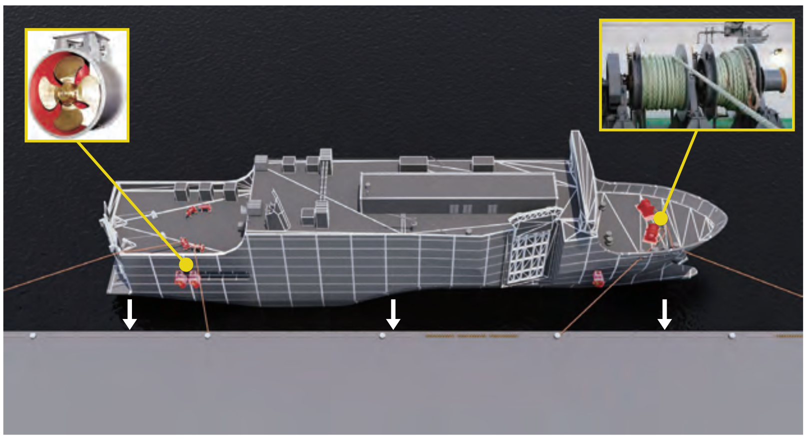

Fig. 5 Mooring operations & management

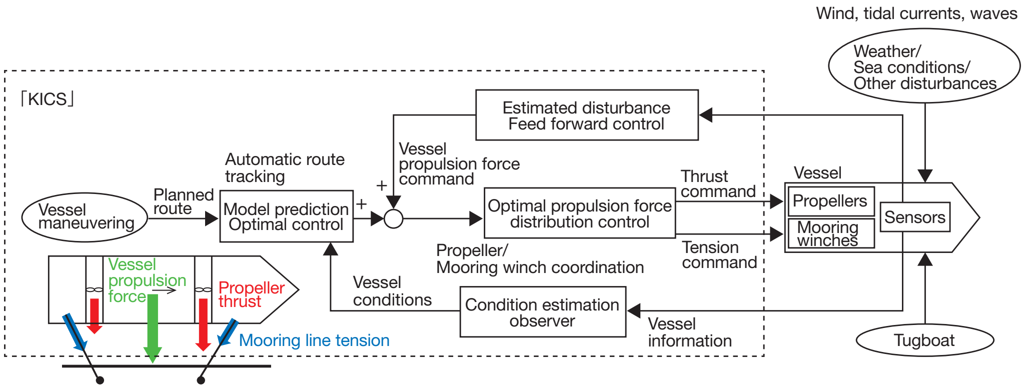

Fig. 6 Control block diagram of KICS (integrated linkage of propulsion and mooring systems)

Fig. 7 Deck machinery

(4) Mooring management

Regarding the management of mooring lines stretched from the bow to the stern of a vessel at mooring, there are needs to reduce the workload of tension state management tasks in response to factors such as tides and changes in the vessel's draft as well as to enhance the safety of these operations.

To meet these needs, we have developed a new system that can detect the tension applied to mooring lines on a vessel while it is at mooring as well as monitor the tension and stress of mooring lines in real time from any location within the vessel. Mooring lines are typically fixed to mooring bollards on the quay side through multiple shipboard fittings. Consequently, there is usually a difference in tension between the mooring winch side and the mooring bollard side. However, by utilizing our unique tension estimation model, we can detect the tension with high precision. This technology contributes to reducing the workloads of tasks such as frequent status checks and tension adjustment operations, particularly in ports with significant tidal variations or rapidly changing vessel drafts. It also enhances safety during mooring.

We have been manufacturing and selling marine hydraulic systems for steering gear and deck machinery (such as anchor windlasses and mooring winches) since we first produced a hydraulic pump for steering gears in 1916. We produce and sell products tailored to various types and vessel categories while developing hydraulic equipment and systems. In the field of deck machinery, our advanced hydraulic control technology contributes to labor saving in cargo handling and mooring operations. We have delivered our products to over 7,000 vessels to date, and they have been highly evaluated by various sectors of the shipbuilding and shipping industries, both domestically and internationally. **Figure 7** shows examples of our deck machinery.

4 Technical verification trial

While proceeding with efforts to convert key technologies into intellectual property for differentiation, we are developing a verification system for the safe berthing and unberthing assist system, aiming for social implementation. **Figure 8** shows the schedule of the

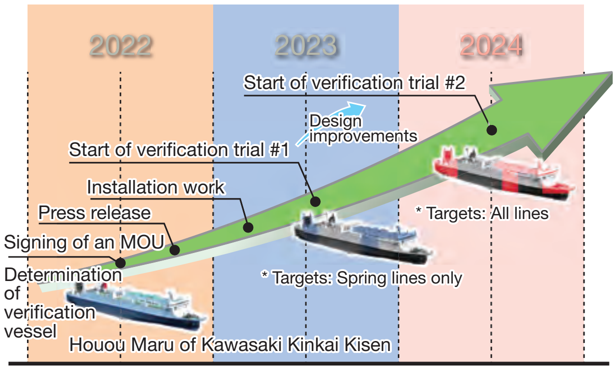

Fig. 8 Schedule of verification trial

verification trial.

For the safe berthing and unberthing assist system, the verification system has been installed on Houou Maru, a roll-on/roll-off coastal vessel that belongs to our co-development partner. We are conducting adjustment of control while collecting data on various actual vessels, including motion models of the vessels, and are scheduled to start the verification trial in October 2023.

Conclusion

We are the only domestic manufacturer capable of producing propellers, DPSs, and mooring winches, which enables us to conduct comprehensive engineering of everything from ship propulsion to mooring. KICS, which is a DPS, can provide integrated control of the propulsion propeller, side thrusters and other propulsion machinery. It comes equipped with a route tracking function that automatically navigates the planned route. To date, KICS has built up an impressive track record in automatic maneuvering technologies in Japan and abroad. Using the control technologies refined with KICS, we will further advance our research and development by utilizing DPS technology and advanced ICT, which we will do to achieve practical application of the integrated linkage of propulsion and mooring systems. Through high-level integration of the results of our research and development with knowledge of safe navigation cultivated by our co-development partners, Kawasaki Kisen Kaisha, Ltd., and Kawasaki Kinkai Kisen Kaisha, Ltd., we aim to achieve consistent safety enhancements from berthing to mooring management, as well as future autonomous vessels, all in the pursuit of marine mobility that is both safe and reliable.

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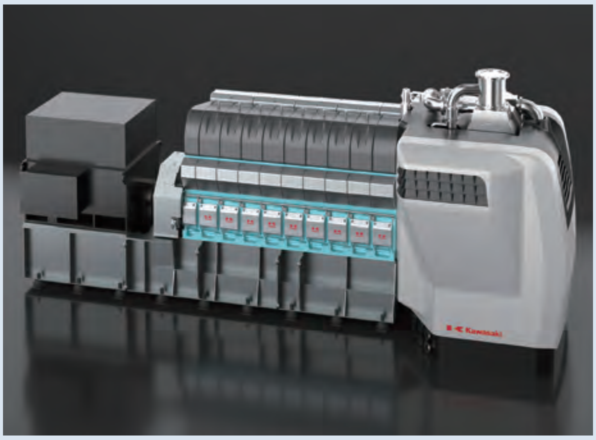
Development of Marine Hydrogen Dual Fuel Engine and Marine Hydrogen Fuel System Promotes a Carbon Neutral Society



In preparation for the widespread use of hydrogen energy in a carbon neutral society, we are developing marine hydrogen engines and hydrogen fuel supply systems as technologies to make use of hydrogen. For long-term demonstration, we will install our marine hydrogen dual fuel engine on a large liquid hydrogen carrier targeting demonstration operation in the 2020s. Also, we will complete the demonstration of the marine hydrogen fuel system (MHFS) by 2030 and are aiming for the commercialization of MHFS.

Introduction

Based on the Paris Agreement adopted in the 2015 United Nations Climate Change Conference (COP21), the International Maritime Organization (IMO) announced that net-zero emissions should be reached in international shipping by 2050 as a GHG emission reduction target, and the announcement gained international consensus.

The Japanese government also aims to reduce CO_2 emissions by 46% by 2030 over 2013 levels and achieve carbon neutrality by 2050. The non-international coastal trading industry, meanwhile, aims to reduce CO_2 emissions by approximately 17% by fiscal 2030 over fiscal 2013 levels.

1 Background

If hydrogen fuel is broadly supplied to the market in response to domestic and international conditions, the market for hydrogen-fueled engines is expected to expand rapidly as the shipping industry aims for decarbonization. At the moment, CO_2 emissions are reduced by improving performance based on natural gas in conjunction with batteries. The coming years, however, should see the commercialization of hydrogen and liquefied fuel co-firing engines, and hydrogen combustion engines that use that technology.

We have begun the development of a Marine Hydrogen Dual Fuel (DF) Engine and a Marine Hydrogen Fuel System (MHFS) after our proposal was accepted by the Green Innovation (GI) Fund, which is operated by the New Energy and Industrial Technology Development Organization (NEDO).

In addition, with the aim of efficiently solving common problems associated with handling hydrogen fuel and helping to promote the use of hydrogen fueled ships in the future, we established HyEng Corporation jointly with Yanmar Power Technology Co., Ltd. and Japan Engine Corporation. Together, we will endeavor to overcome common challenges such as conforming to international rules on hydrogen embrittlement evaluation, hydrogen fuel supply systems, and hydrogen fuels. On the basis of this GI Fund project, each company will develop hydrogen-fueled engines while we develop MHFS.

Of the three companies, we will install and demonstrate our marine hydrogen DF engine on a large liquid hydrogen carrier, targeting demonstration operation in the 2020s with the aim of commercializing it for marine propulsion engines in the future. We will also develop and demonstrate MHFS for the engines of the other HyEng companies and commercialize it after 2030.

2 Development of the Marine Hydrogen Dual Fuel Engine

(1) Development concepts

The main required development concepts are as follows:

(i) Accomplishment of the best hydrogen mixing rate in its size and class

Drastically reduce CO_2 emissions by increasing the hydrogen mixing rate to 95% or higher on a calorific value basis.

(ii) Higher output

Achieve a large 300-mm cylinder diameter with a high mean effective pressure for the sake of higher output per unit cylinder, thereby resulting in a compact and competitive product.

(iii) Application of low-pressure hydrogen gas

Make effective use of boil-off gas—gas generated by the evaporation of hydrogen inside a liquefied hydrogen storage tank—by incorporating a premix port fuel injection function to mix charge air with low-pressure hydrogen gas before they enter the combustion chamber and reduce the power of ancillary gas compressors.

(iv) Application of dual fuel

Incorporate redundancy into the dual-fuel marine engine by making it possible to switch to liquefied fuel if there are operational issues with hydrogen.

Other criteria to meet include which ship classifications to apply the engine to for marine purposes, and emission performance.

(2) Development issues

We developed a natural-gas generator in 2007 and have already sold more than 200 units of it. While developing it, we gained many insights into the reliability of engine control and components. To develop the DF engine, we must solve the following technical issues that arise due to the characteristics of hydrogen fuel.

(i) Suppression of abnormal combustion

When compared to natural gas, which consists mainly of methane, hydrogen has a wide flammable concentration range, requires low minimum ignition energy, and burns rapidly. As such, it is prone to abnormal combustion. The types of abnormal combustion expected to occur are shown in **Table 1**. These may affect stable operation of the engine as well as the engine components. Higher output, one of the concepts, is a key contributor to abnormal combustion, meaning that stable suppression of abnormal combustion is necessary.

(ii) Evaluation of selected materials

Because the combustion chamber and other components are exposed to high-temperature and high-pressure hydrogen fuel and thus subject to hydrogen embrittlement that may lead to the degradation of the material characteristics of the main components, selected materials must be evaluated in a way that takes actual operating conditions into account.

(iii) Obtaining ship classifications

As there are no established ship classification rules for engines that use hydrogen fuel, basic principles such as safety must be evaluated to obtain approval from classification societies.

(3) Development initiatives

(i) Suppression of abnormal combustion

Since abnormal combustion can effectively be suppressed by keeping the oxygen concentration inside the engine low, we adopted and optimized exhaust gas recirculation (EGR). **Figure 1** shows changes made to the firing pressure waveform with different amounts of EGR. Increasing the amount of EGR can reduce the firing pressure and temperature, thereby controlling the characteristically high burning velocity of hydrogen fuel.[1] In addition to EGR, we also optimized the combustion chamber and control logic.

Table 1 Types and symptoms of abnormal combustion

	Type	Symptom
①	Backfire	Backfire from the combustion chamber into the intake piping
②	Preignition	Excess firing pressure resulting from self-ignition of gas before it is ignited in the main combustion chamber
③	Knocking	Excess firing pressure resulting from unburned gas self-igniting near the wall of the combustion chamber, which is far from an ignition source, during expansion

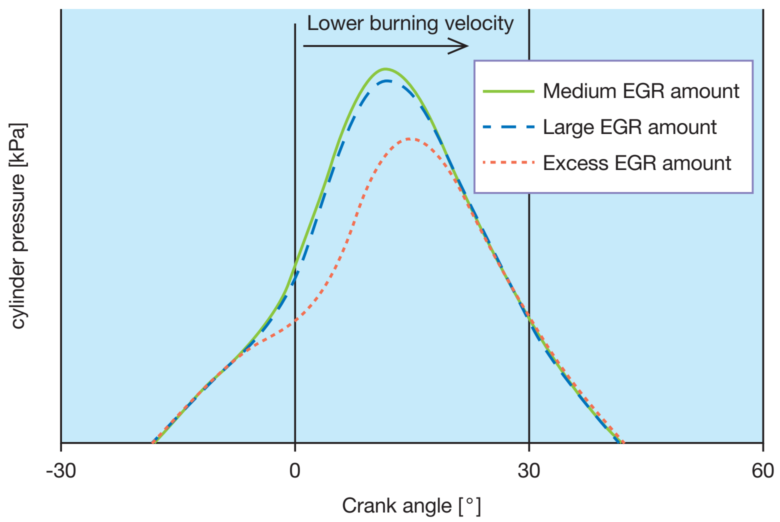


Fig. 1 Differences in peak cylinder pressure by EGR amount

(ii) Evaluation of selected materials

We evaluated materials used as engine parts according to the hydrogen concentrations in various operating environments. Slow Strain Rate Technique (SSRT) tests were conducted to identify environments that significantly affect hydrogen embrittlement, and impacts on fatigue limits and other factors were evaluated. We made sure to conduct these tests appropriately by receiving insights from universities and Nippon Kaiji Kyokai (ClassNK). Going forward, we will test materials in environments where hydrogen fuel is used, as necessary.

(iii) Obtaining ship classifications

As we are cooperating with our ship division on the basic design of the hydrogen DF engine and its ancillary components that will be installed on a large 160,000-m^3 liquid hydrogen (LH_2) carrier, we considered their configuration and layout and worked on the basic design in compliance with the Guidelines for Liquefied Hydrogen Carriers and the IGC Code. From a safety perspective, we also assessed risks using the HAZID study, and confirmed with experts that the ship can be operated safely even if various hazardous incidents occur. As a result, we obtained Approval in Principle (AiP) from ClassNK.

(4) Operating tests

Figure 2 shows the overall development schedule. We will have completed the design of a multi-cylinder engine by fiscal 2023, and will then begin testing it onshore starting from fiscal 2024. Following that, we will design and manufacture marine engines with the test results applied, and install them on a large liquid hydrogen carrier as auxiliary generators for long-term demonstration. **Table 2** summarizes the engine specifications.

(i) Combustion evaluation with single cylinder test engines

Operation of the single cylinder test engines shown in **Fig. 3** was evaluated at Kobe Works and Harima Works. In the testing at Kobe Works, the target mean effective pressure was achieved at a 95% hydrogen mixing rate as originally planned. We will continue to assess the fuel, control, and reliability characteristics of the test engines at

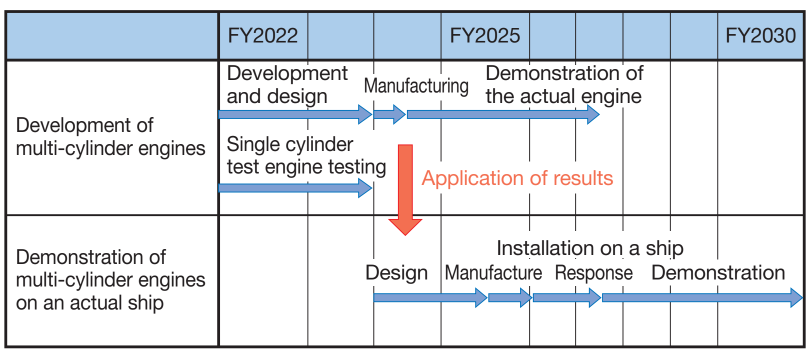
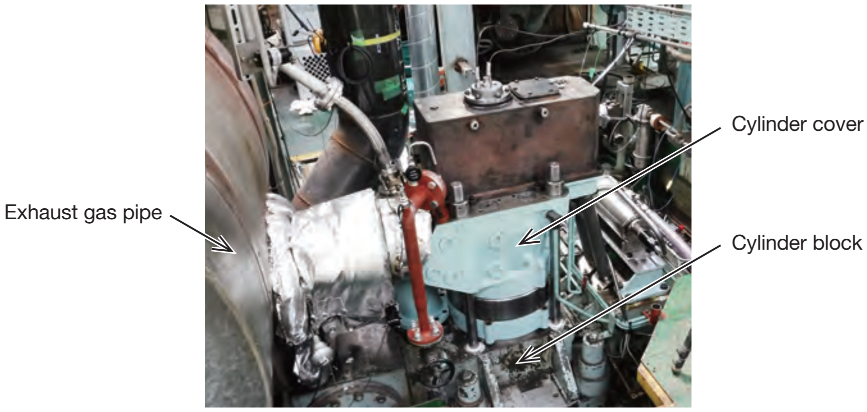


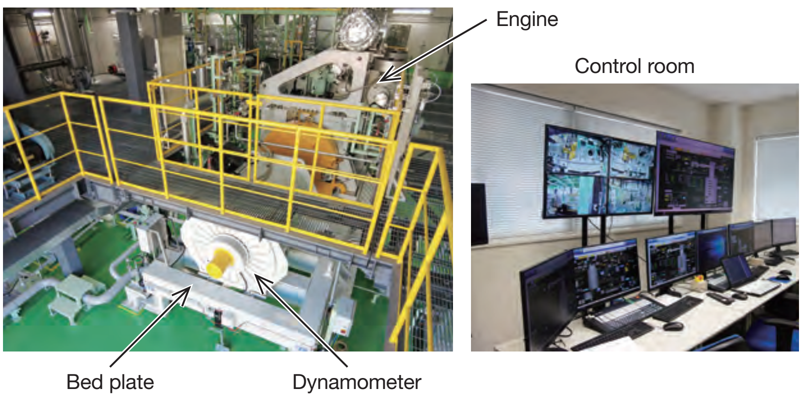
Fig. 2 Overall development schedule

Table 2 Specifications of demonstration engine

Item		Details
Engine specifications	Electric output [kWe]	2, 400
	Cylinder diameter [mm]	300
	Revolutions [1/min]	720
Fuel		Hydrogen fuel (boil-off gas)/low-sulfur fuel oil with the hydrogen fuel accounting for 95% or higher on a calorific value basis
Hydrogen supply pressure [MPa]		1. 0 or less
Emission standards		IMO NOxTier Ⅱ
Authentication		ClassNK



(a) Kobe Works



(b) Harima Works

Fig.3 Single cylinder test engine

the two sites with a view to testing a multi-cylinder engine.

(ii) Onshore engine tests

We will manufacture a demonstration engine, with generators, based on the results of the single cylinder test engines, and test them onshore. Evaluated factors will be the engine's performance and durability and its various functions when it operates on hydrogen fuel. The plan also includes testing a switch between hydrogen and liquefied fuel.

(iii) Long-term demonstration

We will prepare to commercialize the hydrogen DF engine by installing a demonstration engine on a large liquid hydrogen carrier as a generator for supplying the ship with electricity, and demonstrating it on a long-term basis to evaluate its performance and reliability.

3 Development of Marine Hydrogen Fuel System (MHFS)

Two types of MHFSs are under development. One is for middle and high speed 4 stroke hydrogen engines (1-MW class, 1-MPa low pressure (fuel) supply) for ship's electric power generation, and the other is for a low speed 2 stroke hydrogen engine (3-MW class, 30-MPa high pressure (fuel) supply) for ship's propulsion. These two types of hydrogen engines are being developed by other Japanese manufacturers. Each MHFS will be installed on board actual ships and demonstrated by using hydrogen fuel to confirm the safety and reliability as well as the functionalities required for marine purposes. Following completion of the demonstration of the MHFSs by 2030, they will be commercialized for sale after 2030. The goal is the social implementation of MHFS and then to spread the use of liquefied hydrogen fuel in the shipping industry and achieve carbon-neutral marine transportation. An overview of MHFS for 4 stroke hydrogen engines is shown in **Table 3** and **Fig. 4**, with the former providing the particulars and the latter providing a general view of the unit.

Issues regarding the development of MHFS include

- Compliance with the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code)
- Design that can handle hydrogen-specific hazards (such as cryogenic properties, hydrogen embrittlement, permeability, and flammability)
- Confirmation of safety measures based on risk assessments, and implementation of additional measures as necessary
- Technology of vacuum insulation that minimizes heat ingress into liquefied-hydrogen storage tanks and piping
- Consideration of ship-specific phenomena and requirements, such as adaptability to ship's inclinations and swaying motions, sloshing in the tank and rapid change of the amount of hydrogen that the engine consumes, and downsizing for installation on a ship with limited space.

Going forward, we will conduct risk assessments regarding hydrogen hazards in cooperation with the companies involved (shipowners and operators, shipyards, hydrogen engine manufacturers, and Classification Societies) in individual hydrogen fueled ship projects. At the moment, we are working to obtain Approval in Principle (AiP) for the hydrogen fueled ships onto which

Table 3 Particulars of MHFS (for four-stroke engine)

Unit size	40-foot container size
Liquefied hydrogen fuel tank	Approx. 30 m^3, approx. 1 MPaG Horizontal, cylindrical, vacuum multi-layer insulation
Loading limit of LH_2	Approx. 1, 400 kg
Hydrogen gas fuel-supply method	Pressure build-up of LH_2 tank Approx. 0. 7 MPaG, approx. 100 kg/h at normal temperatures

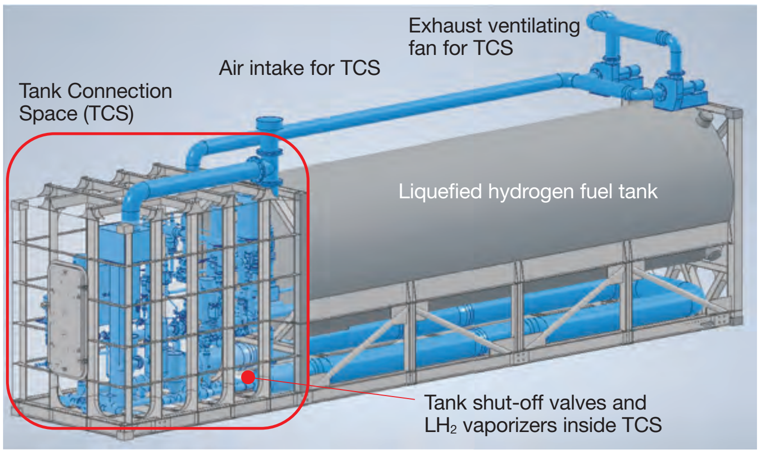


Fig. 4 General view of MHFS unit (for four-stroke engine)

the MHFSs will be installed.

As a shipyard and a manufacturer of marine machinery including engines, we hold a wealth of expertise on ship-related technologies. We can also take full advantage of our broad range of tested and proven hydrogen-related technologies and experience in conjunction with our manufacturing technologies and abilities in making proposals. We will also employ the company's high-precision numerical analysis (simulation) technologies that enable predictions and verifications during the development and design phases, thereby moving the development of MHFS and its demonstration on board actual ships ahead.

Conclusion

To demonstrate our hydrogen DF engine, we will install it on a large liquid hydrogen carrier, targeting operation later this decade. We also expect that HyEng will accelerate the commercialization of marine hydrogen engines and MHFS, and offer our reciprocating engines in the context of using hydrogen.

Note that part of this article was written with assistance from "Development of Technologies for Realizing a Hydrogen Society/Development of Technologies for Large-scale Hydrogen Energy Usage/Development of Technologies Related to High-output Hydrogen Power Generator Systems" and "NEDO Green Innovation Fund Projects/Next-generation Ship Development/Development of Hydrogen Fueled Ships/Development of Marine Hydrogen Engines and MHFS," projects funded by NEDO. We hereby express our cordial gratitude for the contribution.

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SOPass Ship Operation Support System that Optimizes the Economic and Environmental Performance of LNG Carriers

Kawasaki Ecological Frontiers S class†

2022

The demand for natural gas, which is environmentally friendly, is increasing because of the global trend toward carbon neutrality. Also, a greenhouse gas emissions evaluation system has been put into effect in the international maritime industry, and LNG carriers, which play a key role in the marine transportation of natural gas, are required to achieve a good balance between boosting transportation efficiency and evaluating environmental impact. SOPass, which we developed, allows us to respond to these challenges by proposing optimal ship operations based on model calculations and evaluating environmental impact with operational data analysis (CII).

Introduction

Demand for natural gas, which is the most environmentally friendly fossil fuel, is increasing because of the global trend toward carbon neutrality. As LNG carriers are used for long-distance natural gas transportation, such as transportation between continents, because pipeline building is not economical, there is high demand for more efficient long-distance marine transportation of LNG. In particular, a supply and demand imbalance has recently been caused by delays in new LNG export projects, including those related to shale gas in the U.S., and increased demand for LNG in Europe associated with the stoppage of pipeline gas supply due to the Russian invasion of Ukraine. Soaring LNG prices have further increased demand for more efficient natural gas transportation by LNG carriers.

In addition, in the international maritime industry,regulations on a greenhouse gas (GHG) emissions have been implemented. With regard to LNG carrier operations, there is now demand for a ship operation management support system to both boost transportation efficiency and reduce the quantity of environmentally unfriendly substances, evaluating the results of these measures as indices.

1 Background and history

Around the year 2000, we developed and began to provide a ship operation support system that makes use of communication between ships and land. First, we developed a system that analyzes the performance of the main engine and that monitors the machinery part in general cargo ships on land. We then developed and provided a wide range of ship operation support systems, including a vessel performance analysis system for LNG carriers and an optimal route calculation (weather routing) system for general cargo ships.

In 2016, we released a ship operation management support system for LNG carriers, SOPass (Ship Operation and Performance analysis system), and we started to provide service in 2017, anticipating needs for efficiency improvement in marine transportation of LNG.

SOPass was developed to support charterers who are involved in the operation management of LNG carriers on land as key players in natural gas transactions. SOPass is equipped with various applications that can be used seamlessly from before, during, and after voyages. By providing a future prediction function and an evaluation function in addition to a function to check the statuses of ships in real time, we aimed to enable the service to

† A ship operation management support system that merges real data from a ship with engineering insights from the shipyard to analyze data and to predict the future in order to support efficient ship operation.

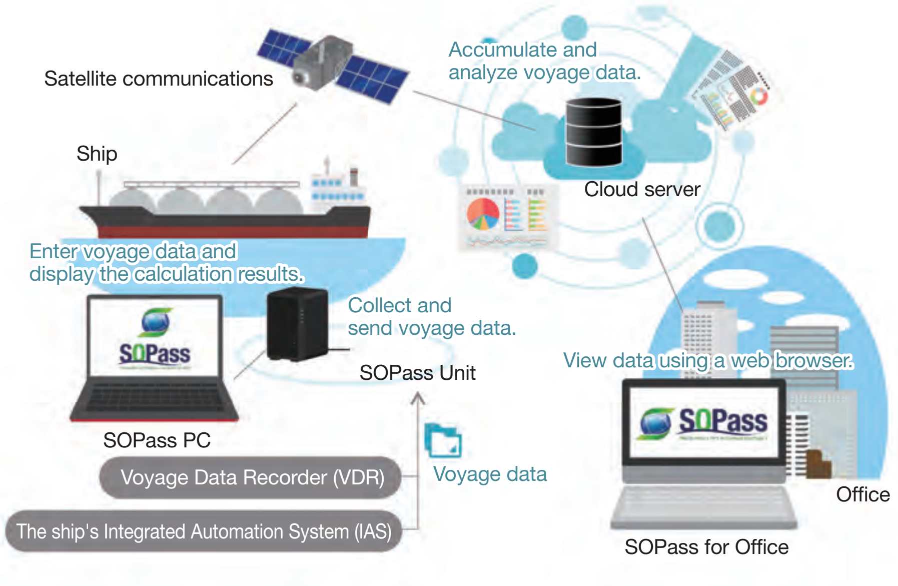

Fig. 1 System configuration and data flow schematic

identify and examine future actions for ship operations without requiring advanced expertise and many years of experience.

Fig. 1 shows the system configuration and data flow schematic of SOPass. SOPass collects ship operation data in a datacenter on land via satellite communications, analyzes the data according to the purpose of application, and computes a model simulation to predict future voyages. The SOPass user can view the operation status and analysis results of the main ship via a web browser at any time, anywhere.

2 Challenges that SOPass can solve

(1) Improvement of the transportation efficiency of LNG carriers

Some challenges are specific to laden and ballast voyages.

One challenge for laden voyages is to productively use NBOG (Natural Boil Off Gas) as propulsion energy or electricity on board. NBOG is a gas generated from LNG in the cargo tank when it partly vaporizes due to heat input from outside. During a voyage, the inner pressure in the cargo tank must be properly controlled by extracting this gas to decrease the pressure in the cargo tank, which rises due to NBOG. The extracted NBOG is used as fuel for the main engine. If the ship is not equipped with a reliquefaction system, extra NBOG that cannot be consumed due to the main engine's output status is wastefully burned in the combustion unit. The operation plan with the highest transportation efficiency consists of main engine output that is maintained so as to balance the amount of NBOG extracted from the cargo tank with the main engine's NBOG consumption, the vessel speed obtained based on the output of the main engine and the route, and the ship operations obtained by considering these in a composite way.

One challenge for ballast voyages is to determine the exact amount of LNG (amount of heel) that should be left in the cargo tank to cool the cargo tank and to be used as fuel for propulsion and power generation. To maximize the LNG discharge amount at the end of a laden voyage, it is desirable to reduce the amount of heel for the next ballast voyage as much as possible. However, because the necessary amount of heel during a ballast voyage differs by cargo tank type, the number of voyage days, and fuel consumption for the route, these factors must be sufficiently considered when determining the exact amount of heel. Another challenge is how to productively use the SBOG (Spray Boil Off Gas) generated when LNG sprayed in the cargo tank to cool it vaporizes as propulsion energy and electricity on board.

To address these challenges, we must make it possible to propose optimal plant operations and routes for LNG carriers, thus constraining the loss of LNG, their cargo.

(2) Environmental impact evaluation of LNG carriers

In the international maritime industry, which has implemented measures to reduce GHG emissions, the evaluation of ships' GHG emissions is an urgent challenge. Since the international evaluation system for the environmental impact during ship operation started in 2023, in the industry's efforts toward carbon neutrality, visualization of ships' actual fuel efficiency for evaluation is gathering much attention.

The CII (Carbon Intensity Indicator), which serves as an evaluation index for LNG carriers, can be expressed by the following equation.

$$\mathrm{CII} = \frac{CO_2 \text{ emissions [g]}}{\text{Deadweight (DWT) [MT]} \times \text{Actual navigation distance [NM]}}$$

MT：Metric Ton
NM：Nautical Mile

A carbon intensity rating of A to E is determined according to the attained CII. If a ship has a low carbon intensity rating, the shipowner must create an improvement plan for the ship and obtain approval from the authority. In addition, because the International Maritime Organization (IMO), which established this system, encourages parties in the maritime industry, including the main supervising agency and port authorities, to reward ships that have high carbon intensity ratings, it has become important in relation to ship operations to monitor the attained CIIs and to improve carbon intensity ratings.

In addition, companies in the international maritime industry have established the Sea Cargo Charter for cargo owners and maritime companies to evaluate and announce how well operating ships are meeting the IMO's GHG emissions reduction goal, and they have established the Poseidon Principles for financial institutions' ship loan portfolios. Therefore, evaluation of GHG emissions from ship operations can be considered a maritime-industry-wide challenge.

3 Problem-solving processes using SOPass

(1) Efforts to boost the transportation efficiency of LNG carriers

We have developed BOG-Navigation, which is a function that contributes to improving the efficiency of marine transportation of LNG, by combining the optimal route calculation technology and the operation data analysis technology we have created through past system development, operational insights from the construction of LNG carriers, our thermodynamic evaluation technology, and more.

(i) Prediction of ship motion and LNG state

SOPass can predict the amount of increase in the ship resistance and the swing of the ship as a result of changes in marine climate conditions based on the vessel performance model constructed using design data during ship construction. As shown in **Fig. 2**, the system can predict the amount of increase in the resistance according to the cycle and direction of waves to which the ship is subjected at a given vessel speed, using the vessel

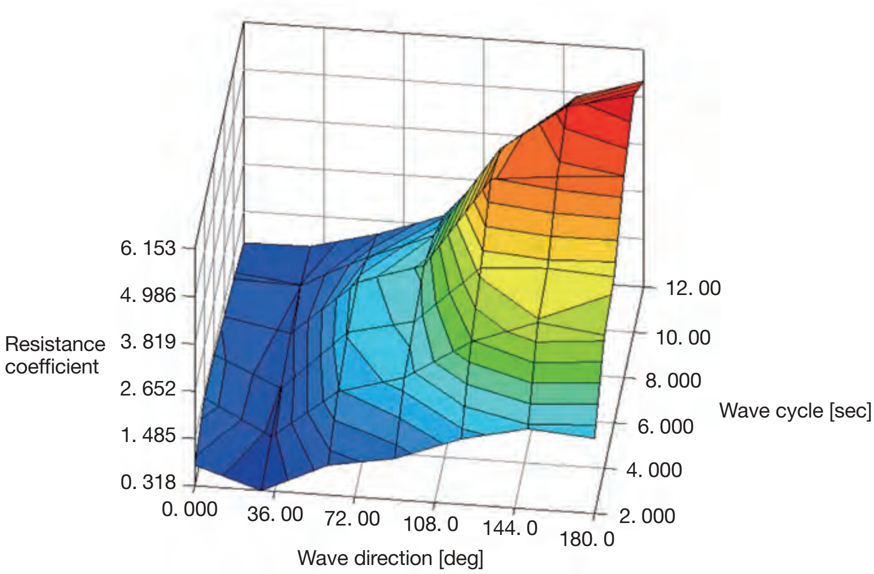

Fig. 2 Amount of increase in resistance in irregular waves at a certain vessel speed

performance model to predict the amount of increase in the resistance due to waves. In addition, the system can calculate the shaft output, number of propeller revolutions, vessel speed, and fuel consumption required for ship propulsion by predicting the wind resistance against the ship, wave-making resistance, viscosity resistance, and other factors. It can also predict the motion of the ship in waves and wind, such as rolling and pitching.

Furthermore, the system can predict the states of the cargo tank as well as the liquid and vapor inside the cargo tank based on the cargo tank heat transfer model constructed with consideration given to structural factors such as the hull, tank, and piping. Moreover, it can predict the pressure in the cargo tank and the amount, temperature, and composition of LNG, which changes from hour to hour in response to the ambient air temperature, sea temperature, and heat intrusion, such as solar radiation. **Fig. 3** shows the calculation result of the solar radiation impact using a heat transfer model constructed using the design data of an LNG carrier that we built. The amount of NBOG and SBOG generated in the cargo tank as well as the equator temperature for Moss tanks and the LNG temperature at each liquid level for membrane tanks can also be predicted.

By making it possible to predict the ship motion and LNG state through model simulation, the statuses of LNG carriers during voyage can be predicted.

(ii) Proposal of ship operations for higher transportation efficiency

We have developed the BOG-Navigation function to propose ship operations that improve the transportation efficiency of LNG carriers by combining the LNG carrier plant operation technology we have accumulated as a shipyard, prediction data on the statuses of LNG carriers through the model simulation described in section (i), and weather routing technology.

BOG-Navigation predicts elements such as the amount of generated NBOG, changes in tank pressure, and changes in LNG composition (aging) during laden voyages using marine weather forecast data as an input to calculate the hourly amount of energy that can be used as fuel for propulsion during a voyage. This function has succeeded in boosting the transportation efficiency of each voyage by presenting plant operations and a route by which the available energy is not wasted. Because BOG-Navigation can predict ship motion according to marine climate conditions in addition to the LNG state, the user can set upper limit values for the wave height as well as rolling and pitching angles during the voyage to limit operations and utilize information on the safest, most fuel-efficient route and prediction information on the ship operation status for the voyage. The user on land can share this voyage prediction information with the main ship by web browser. In addition, BOG-Navigation automatically calculates a plan from the current position of the main ship to the destination port and provides it to the user on land and the main ship daily as shown in **Fig. 4**. The user on land can share voyage prediction information that is continuously calculated using the latest marine weather forecast data with the main ship.

In addition, the amount of heel required for ballast voyages can be estimated based on the optimal cooling spray pattern as well as the cooling spray amount and fuel consumption required for the voyage predicted using the model described in section (i). The LNG discharge amount can be maximized by predicting and presenting the minimum necessary amount of heel for the next ballast voyage when a laden voyage is completed.

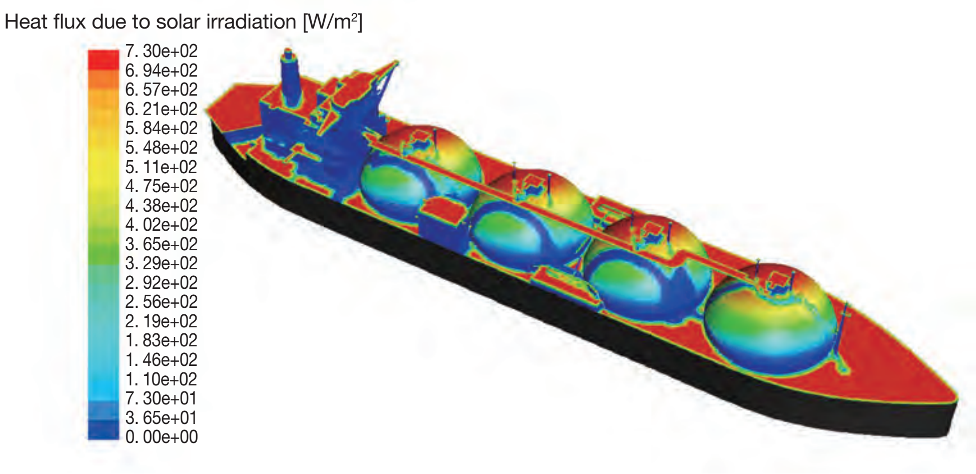

Fig. 3 Solar radiation impact calculation by heat transfer model

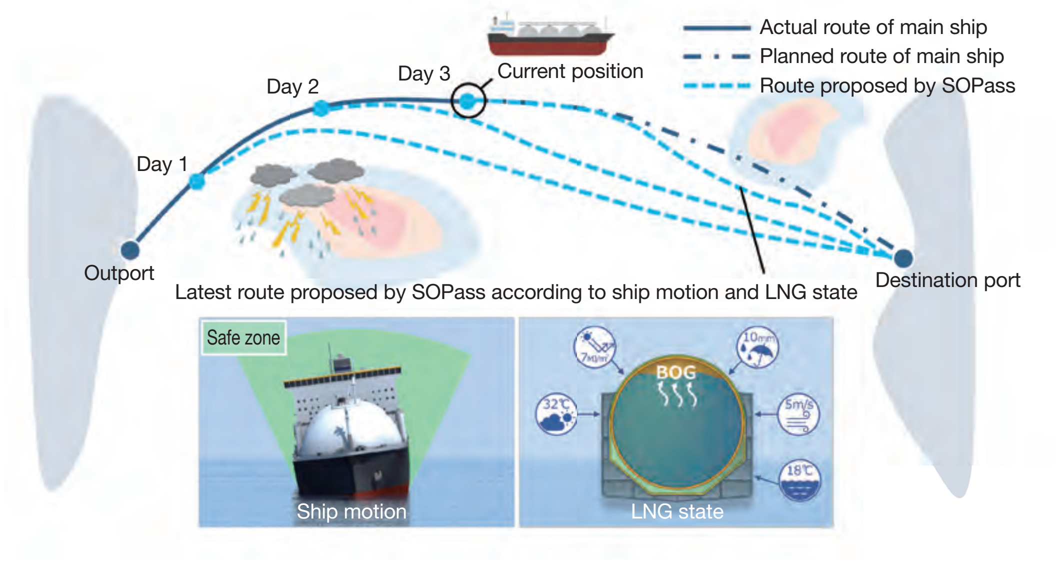

Fig. 4 Outline of periodic calculation by BOG-Navigation

(2) Efforts to evaluate the environmental impact of LNG carriers

Under the CII regulation, to determine the carbon intensity rating, attained CIIs calculated based on the actual operation data for one year are evaluated. Actual operation data—such as the type of fuel used by the ship, fuel consumption, and navigation distance—is required to calculate the attained CIIs. For SOPass, we developed CII Evaluation to estimate ships' CO_2 emissions and the trend in attained CIIs from such actual operation data in order to provide CII evaluation information that is continuously calculated from the latest actual operation data.

On the CII evaluation information display screen shown in **Fig. 5**, the attained CII (①) and CO_2 emissions (②) of each voyage can be displayed in addition to these values per annum, which is the CII regulation's evaluation period for evaluating the environmental impact of each voyage. The screen also has a section (③) to check to what extent the navigation distance and CO_2 emissions must be changed to improve the carbon intensity rating. This section can be used to examine the operation method in order to improve the rating.

In addition, there is a screen that displays the trend graph for CO_2 emissions and attained CIIs at 30-minute

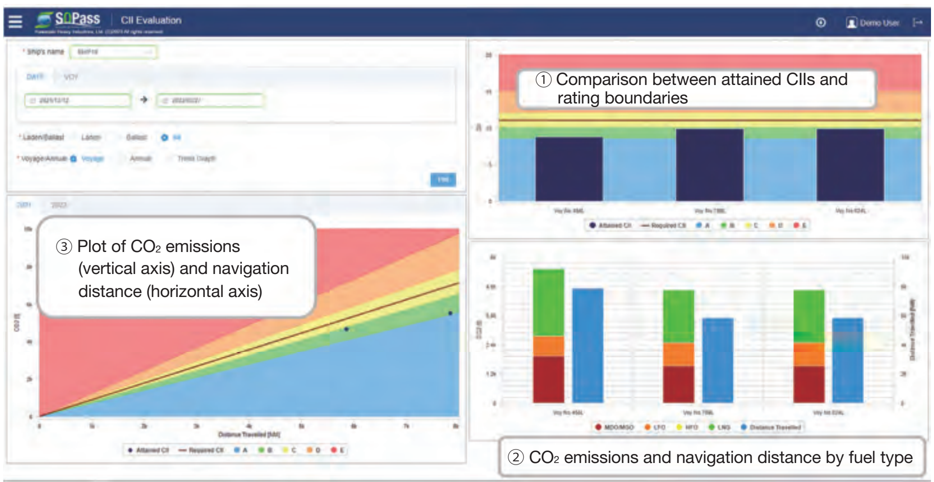

Fig. 5 Representation of CII evaluation information for each voyage

intervals. This graph can be checked against the trend graphs of marine climate data and actual past operations provided by SOPass to analyze why the attained CII fell during a voyage and to improve the operation method.

Conclusion

BOG-Navigation, which supports future voyage planning, is a proprietary function we have developed by leveraging our strengths as a shipyard and advanced thermodynamic evaluation technology. We will work on future prediction using machine learning to achieve highly practical operation support in order to predict the future operation statuses of ships more accurately.

We are considering leveraging SOPass to boost the transportation efficiency of liquefied hydrogen carriers in transporting hydrogen, which we are examining as a source of zero emissions energy, by developing this technology going forward.

In addition, regarding CII Evaluation, which provides only evaluation information for actual values at present, we aim to release a function to predict future CII evaluation values based on actual operation data and future voyage schedules at an early date.

We will continue to carry out aggressive development by combining our technologies to extend the functionality of SOPass and contribute to further efficiency improvements in marine transportation and GHG emissions reductions across the international maritime industry.


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Development of Autonomous Underwater Vehicle (AUV) with Robot Arm SPICE

In the offshore development business, including offshore oil and gas field development, as well as in other businesses, it is required to enhance operating efficiency and reduce environmental impact, and as a solution to it, there are increasing expectations for the commercialization of autonomous underwater vehicles (AUVs). In response to such expectations, we have developed SPICE, an AUV that is equipped with a subsea docking station and a robot arm for inspecting subsea pipelines.

Introduction

Recently, in the offshore development business, including offshore oil and gas field development and offshore mineral resource development, as well as in other businesses, it is required to enhance operating efficiency and reduce environmental impact [1].

1. Background and aim

In the offshore development business, including the development, construction, and maintenance of offshore oil and gas fields and exploration of offshore mineral resources, remotely operated vehicles (ROVs) have been used to explore the seabed, and construct, inspect, and maintain subsea structures. Because of the recent oil price drop and increasing interest in environmental impact, and thanks to the progress of technology in the field of autonomous underwater vehicles (AUVs), it is increasingly expected that operating efficiency will be enhanced by automating part of ROV operation with AUVs and CO_2 emissions will be reduced by reducing the operating time of the support vessel with the enhanced operating efficiency. AUVs, unlike ROVs, do not require operators with advanced skills and their movement is not restricted by wires. Also, ROVs require support vessels with advanced dynamic positioning capabilities to operate, but AUVs can be operated with simpler support vessels. We began the research and development of AUVs in 2013 by taking advantage of the underwater vehicle and equipment technologies we have accumulated for many years in building submarines and deep submergence rescue vehicles.

2. Product concept and technical challenges

In addition to our unique underwater docking technology, we developed underwater power transfer and underwater optical communication technologies, which are fundamental technologies to operate AUVs continuously without retrieving them. Also, aiming to enter the oil and gas industries, we developed technologies to enable close-range inspection that conventional AUVs cannot perform, including pipeline tracking systems and robot arms for inspection, and successfully commercialized SPICE (Subsea Precise Inspector with Close Eyes), which is an AUV for pipeline inspection [2].

Based on the results of comparison of advantages and disadvantages with ROVs, which are now commonly used in offshore exploration, and interviews with pipeline inspection companies, we set the following as technical challenges for commercialization.

- Because the operating time is restricted by the battery capacity, underwater station docking technologies are required, including underwater charging systems.
- Because real-time monitoring and instruction are

† System that is designed for the close-range inspection of subsea pipelines and other infrastructure and that consists mainly of autonomous underwater vehicles, support vessels, and stations

impossible, new technologies are required to autonomously search for and track pipelines and control robot arms.

3. Details of element technologies and problem-solving process

(1) Underwater station docking technology

Conventional AUVs are retrieved and charged on the vessel when they run out of battery. However, if AUVs can be docked to an underwater station for charging and data transfer, they can inspect subsea pipelines almost permanently without being retrieved, which provides enhanced safety in offshore operations. This technology can be applied to stations installed at the seabed. It can also be used for systems that periodically conduct patrol inspection in a certain area around a station with adequate power supply and communication. **Figure 1** shows how an AUV is docked to an underwater station.

(i) Underwater docking [3)]

The AUV performs a docking sequence in two steps. In the first step, the AUV catches the pole installed on the station. The AUV moves guided by the acoustic signals from the transponder mounted at the tip of the pole. When the AUV approaches the station, it detects the omni-directional light source mounted at the base of the pole. The AUV moves toward the light source and grabs the pole with the concave hardware mounted on the front of the AUV. In the second step, the AUV turns around the pole it has grabbed and moves up and aligns the convex mating hardware mounted on the top of the AUV with the mating device on the station to dock with the station. For this positioning process, a pair of optical communication devices mounted on the AUV and station are utilized.

(ii) Underwater charging and data transfer

The AUV starts charging the battery after it docks with the station. For underwater power transfer, both the AUV and station have a pair of wireless power transfer pads. During docking, these pads are kept a few centimeters apart, and power is transferred by electromagnetic induction with an efficiency of 90% or more.

While the battery is being charged, the inspection data acquired during subsea pipeline inspection, including videos and images, are transferred via the optical communication device used for docking.

(2) Pipeline search and tracking technology

The AUV recognizes its own location to approach a subsea pipeline, performs a pipeline search, and tracks and inspects the pipeline by tracing the pipeline with the body and arm.

(i) Subsea self-location recognition

Some subsea pipelines are installed at a water depth of more than 3,000m. To inspect such deepwater pipelines, AUVs are required to constantly recognize their own location while in the water, and the inertial navigation system (INS) carries out this function. The INS estimates the location of the vessel based on the acceleration and attitude acquired from sensors, but errors are accumulated because AUVs operate underwater for several hours. In the water, unlike on land, the location of the vessel cannot be measured with GPS or the like, and therefore, correction is made from the support vessel by using acoustic positioning and acoustic communication.

(ii) Pipeline search

After the AUV reaches the seabed, it moves toward the estimated location of a pipeline, from the side of the pipeline, and from a location some distance from the

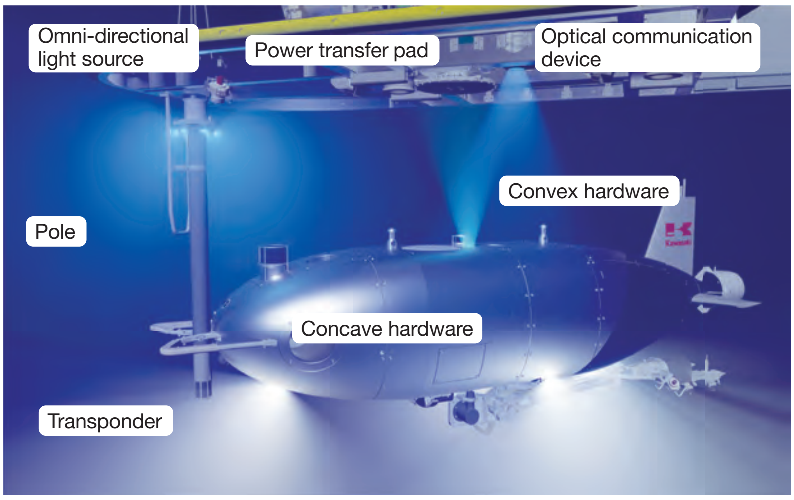

Fig. 1 Docking between AUV and underwater station

pipeline. The AUV performs seabed mapping with a multi-beam sonar. A linear gradation pattern is observed when the AUV passes over a pipeline, which is processed by image processing technology to identify the exact location of the pipeline.

(iii) Pipeline tracking

After identifying the location of the pipeline, the AUV starts pipeline tracking from a few meters above the pipeline in the predetermined direction. In pipeline tracking, as shown in **Fig. 2**, the multi-beam sonar used to search for pipelines is used to detect the cross section of the pipeline and the seabed as a semicylindrical shape. This semicylindrical shape is followed to track the pipeline. At the same time, the robot arm is controlled in consideration of the position, speed, and altitude of the AUV to guide the tip of the robot arm precisely to the proximity of the pipeline [4).

(3) Robot arm control technology

As a technology to precisely locate the sensors, including the cameras, close to the pipeline for underwater close-range inspection, we developed a robot arm specially designed to be installed at the bottom of the AUV.

(i) Structure

The structural members must be lightweight and able to be used for subsea operation in order to be installed on the AUV, and therefore, they are made mainly of corrosion-resistant aluminum alloy. In addition, bearings and actuators have been adopted that can withstand use in the sea.

The robot arm is designed to have six degrees of freedom with six axes so that the sensors can be located close to the pipeline with the robot arm tip in any position or posture as shown in **Fig. 3.** Three axes at the AUV side are controlled actively, and the other three axes at the tip of the arm have a passively controlled link structure, which allows the sensors to smoothly track the pipeline to be inspected. This simplified structure has provided a reduced weight and control load.

(ii) Control

Unlike the robot arms secured to the ground, this robot arm is installed onto an AUV, which is constantly moving. Therefore, we developed a logic to control the tip of the robot arm in consideration of the position coordinates detected by the moving AUV and the future position and attitude of the AUV so that the tip of the robot arm is always directed toward the pipeline and stays over the pipeline even if the AUV moves away from the pipeline as shown in **Fig. 4.**

(iii) ITU (Inspection Tool Unit)

We developed an ITU for enabling the sensors mounted at the tip of the robot arm to track the pipeline safely and reliably. The ITU has stabilizing fins for generating a pushing force against the pipeline by using the water stream generated during operation and sensors and damping mechanisms for preventing excessing pushing and mitigating damage caused by collision with obstacles and other objects. The ITU is installed at the tip of the robot arm so that the sensors installed on the ITU can be kept close to the pipeline in a stable posture while the AUV is moving over the pipeline. This provides accurate and precise inspection data that conventional AUVs cannot achieve [5).

(iv) Verification

SPICE is the world's first AUV equipped with a robot arm, and we had many challenges with how to verify the robot arm in the processes from design, production, and

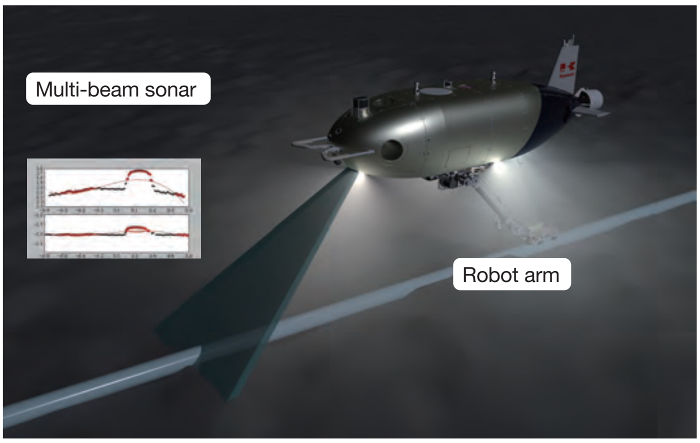

Fig. 2 Pipeline tracking

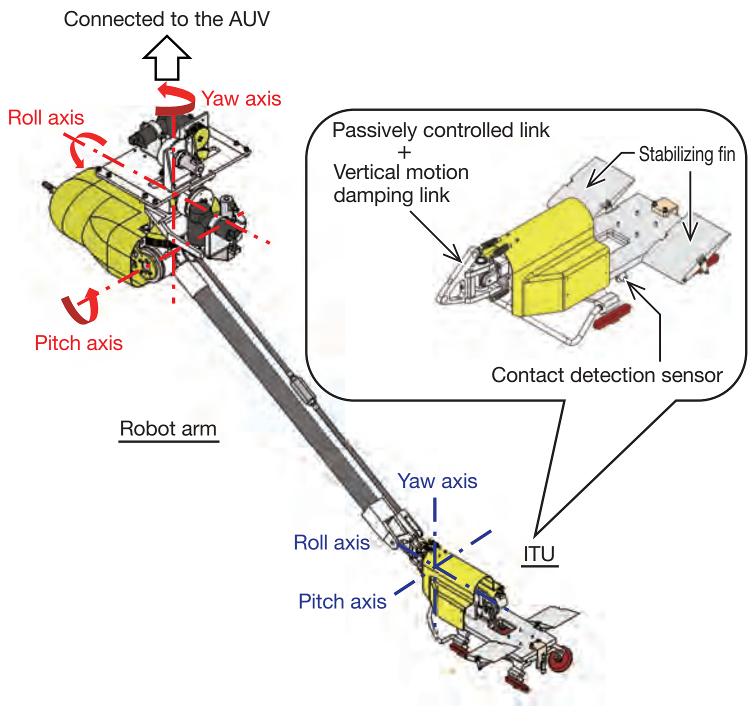

Fig.3 Structure of robot arm

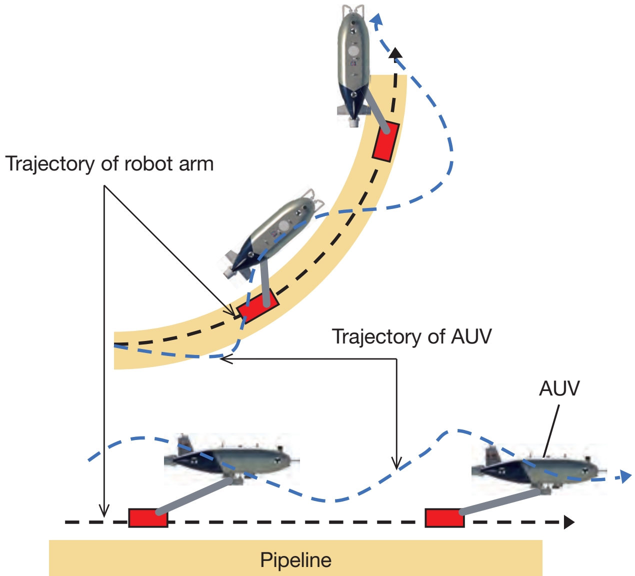

Fig. 4 Pipeline tracking by AUV [2)]

testing to installation on the AUV. Using the robot technologies we have accumulated, as shown in **Fig. 5**, we installed the robot arm designed for AUVs onto the tip of an industrial robot and verified the motion of the robot arm following the motion simulating an AUV, which allowed us to conduct element tests efficiently and reach operational verification testing earlier than anticipated.

Also, through various tests, our AUV exhibited stable pipeline tracking capabilities and a high potential as a platform for subsea pipeline close-range inspection, attracting attention in the oil and gas field. In September 2022, we conducted offshore testing using SPICE as part of joint research with TotalEnergies SE, which is a French energy supermajor, on protective potential measurement in subsea pipeline close-range inspection, which ended in success (**Fig. 6**) and demonstrated SPICE's usability [6)].

Fig. 5 Simulation of robot arm tracking operation using an industrial robot

Fig. 6 Successful offshore testing jointly with TotalEnergies

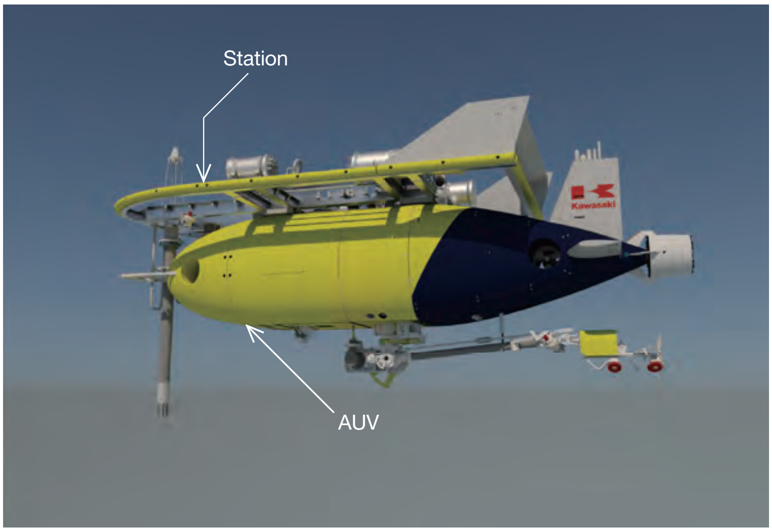

Fig. 7 First commercial AUV

Table 1 Principal particulars of first commercial model

	AUV	Station
Total length [m]	5. 6	5. 6
Total width [m]	1. 3	2. 0
Total height [m]	1. 5	2. 6
Weight in air [tons]	Approx. 2. 5	Approx. 1. 2
Operational water depth [m]	3, 000（max）	500（max.）
Battery	Lithium polymer battery	–
Speed [knots]	4. 0（max.）	–
Operation time [hours]	10（inspection work）	–
Charging time [hours]	3（underwater）	
Wireless charging system [kW]	10	
Optical wireless communication [Mbps]	100	

4. Delivery and introduction examples

In 2020, we received an order for the first commercial model of SPICE (**Fig. 7**), which incorporates these technologies, from a British pipeline inspection company [7]. **Table 1** shows the principal particulars of this model. This commercial model can operate at a water depth of up to 3,000 m and perform pipeline inspection at a speed of 2 knots for 10 hours. The station can operate at a water depth of up to 500 m, which helps reduce battery power consumption while the AUV is operating. In addition, the underwater charging system has a capacity of 10 kW and can charge the AUV in only three hours.

Conclusion

We developed technologies aimed at automating pipeline inspection using AUVs and in the pipeline tracking verification test, received a high evaluation from an oil major. We are about to reach the commercialization stage.

Expanding their applications to floating offshore wind farms and other facilities, we will develop AUVs and inspection methods that meet the needs of the facilities to be inspected, by taking advantage of the AUV and robot arm control technologies we have accumulated with AUVs for pipeline inspection. Also, we will aim to develop AUVs that can be operated safely while satisfying the body requirements and operational requirements given in the "Guidelines for Safe Operation of AUVs," issued by the Ministry of Land, Infrastructure, Transport and Tourism.

Finally, we would likely to thank The Nippon Foundation, which provided subsidies to develop a robot arm for inspection and conduct demonstration experiments for pipeline tracking, and the Ministry of Land, Infrastructure, Transport and Tourism, which provided subsidies to develop inspection sensors and their data processing.

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3) Patent No.GB2579951, "Charging system for autonomous underwater vehicle and method of lifting and recovering autonomous underwater vehicle"

4) International application No.PCT/JP2021/010499, "Submersible vessel (arm collaborative control for autonomous underwater vehicles)"

5) International application No.PCT/JP2019015651, "Autonomous underwater vehicle (main body and arm structure that provide enhanced pipeline tracking)"

6) "Kawasaki has successfully verified the Close-range Subsea Pipeline Inspection by Autonomous Underwater Vehicle (AUV)," press release by Kawasaki Heavy Industries, Ltd., July 15, 2020

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Kawasaki Green Gas Engine Cogeneration System

Cogeneration systems that integrate our Kawasaki Green Gas Engine, which is fired solely by city gas/ natural gas, are often installed to reduce energy consumption throughout facilities, including that of heat recovery. The latest model of the Kawasaki Green Gas Engine achieves a power generation efficiency of 51.0%, a global best-in-class level, and it is increasingly being installed as a BCP measure as a hedge against disaster. It supports quick start-up, low-load operation, and frequency fluctuation, and we have also established a 30 vol% hydrogen mixed-fuel combustion technology. In addition, gas engines hold great promise as a product to help promote the use of renewable energy to achieve a carbon neutral society by 2050.

Introduction

At the 26th Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change (COP26), Japan pledged to reduce its CO_2 emissions by 46% by FY2030 compared to the FY2013 level. While promoting the use of renewable energy has widely been highlighted as a means of achieving carbon neutrality, expectations are increasing for gas engine power generation, not only as a BCP measure in the event of a disaster, but also as a way to flexibly handle the variance in power supply from renewable energy sources.

1 Background

Cogeneration systems using gas engines, which enable high economic efficiency and energy savings as combined heat and power systems that generate electricity and effectively utilize waste heat on the demand side, have become popular. As of December 2022, orders for our Green Gas Engine have reached 224 units, providing a total power generation capacity of 1,684 MW.

2 Product overview

For our top-selling KG-18-V, the recovery rate at 100% energy input is 49.5% for electricity, 15.2% for steam, 13.4% for high-temperature water, and 4.0% for low-temperature hot water, achieving an overall efficiency of 82.1% (conditions: city gas; 0.784 MPaG saturated steam; high-temperature water recovery [75°C (inlet) / 90°C (outlet)]; and low-temperature hot water [25°C (inlet) / 60°C (outlet)]). The steam is used as a heat source for heating in the production process; the high-temperature water is used as a heat source for a hot water absorption chiller; and the low-temperature hot water is used for heating utilities and other purposes.

3 Product features

(1) Global best-in-class level of power generation efficiency and environmental performance

The Kawasaki Green Gas Engine lineup consists of the five types shown in **Table 1**, and the latest model KG-18-T, which adopts two-stage turbocharging, has achieved a power generation efficiency of 51.0%, a global best-in-class level. The KG-18-T adopts our technology for low NOx emissions of 200 ppm or less (O_2 = 0%), a quantity that in many regions does not require a selective catalytic reduction device.

As shown in **Fig. 1**, the KG-18-T is the first gas engine in its class in Japan to introduce a two-stage turbocharging system that features two turbochargers and two air coolers as a module to improve turbocharger efficiency, thereby enabling a substantial increase in power generation efficiency.

Table 1 Lineup of Kawasaki Green Gas Engines

		「KG-12」	「KG-18」	「KG-12-V」	「KG-18-V」	「KG-18-T」(Two-stage turbocharging)
Number of cylinders		12	18	12	18	
Electric output〔kW〕	50Hz	5, 200	7, 800	5, 200	7, 800	
	60Hz	5, 000	7, 500	5, 000	7, 500	
Power generation efficiency〔%〕		49. 0		49. 5		51. 0
NOx〔ppm〕		200 or less（O_2 = 0%）				

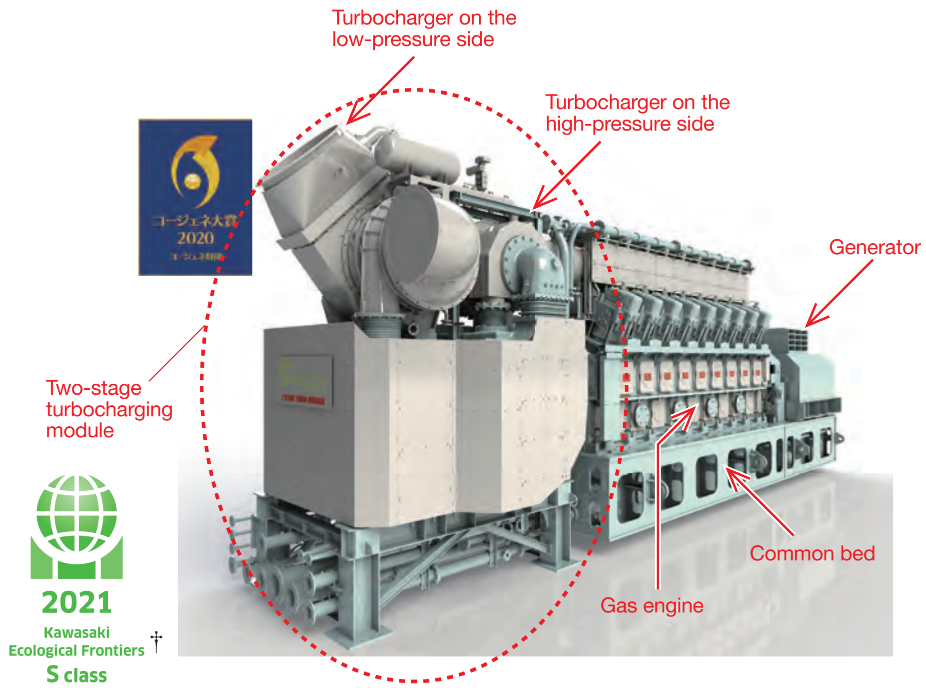

Fig. 1 Two-stage turbocharging gas engine (KG-18-T)

In recognition of these features, it has received numerous awards, including the Chairman's Award in the Technological Development Category at the 2020 Cogeneration Awards hosted by the Advanced Cogeneration and Energy Utilization Center Japan, and the Agency for Natural Resources and Energy Commissioner's Award at the FY2022 Energy-Saving and Decarbonization Machinery and Systems Award hosted by the Japan Machinery Federation.

† New high-performance Green Gas Engine equipped with an 8-MW-class two-stage turbocharging system, which achieves the world's highest level power generation efficiency among engines of the same capacity and significantly reduces fuel gas consumption

(2) Quick start-up

While the normal start-up time is ten minutes or less from issuance of the start-up command to reaching the rated load, the time is reduced to five minutes or less by using the quick start-up system, which employs compressed air to assist turbocharger rotation to maintain stable turbocharger pressure and to prevent abnormal combustion due to load increase.

(3) Wider range available in low-load operation

In response to market demand, we have expanded the available range in the low-load combustion operation from the conventional 30% load to 20% load. As a result, the ability to adjust the supply-demand balance has been improved, in addition to improved start-up performance.

(4) Support for frequency fluctuation events

The blackout caused by the Hokkaido Eastern Iburi Earthquake has increased the need to improve the tolerance to possible frequency fluctuations. To meet this challenge, we introduced a new evaluation of dynamic characteristics when the frequency drops, thus enabling all models to operate even when the frequency drops to 94% of normal, thereby contributing to stabilizing the frequency of the power grid.

(5) Establishment of 30% hydrogen mixed-fuel combustion technology

We have established a system that can appropriately control the combustion state according to the power generation output and the hydrogen mixture ratio, and we conducted hydrogen mixed-fuel combustion tests and other tests using a single-cylinder demonstration unit. As a result, we became the first Japanese gas engine manufacturer to develop a combustion technology that enables stable operation of large gas engines with a power generation capacity of 5 MW or more by mixing up to 30% by volume of hydrogen with natural gas. In hydrogen mixed-fuel combustion, safety measures against hydrogen leakage are important, so we equipped the demonstration unit with a system for safely venting any leaked hydrogen around the combustion chamber to the outside, as shown in **Fig. 2**.

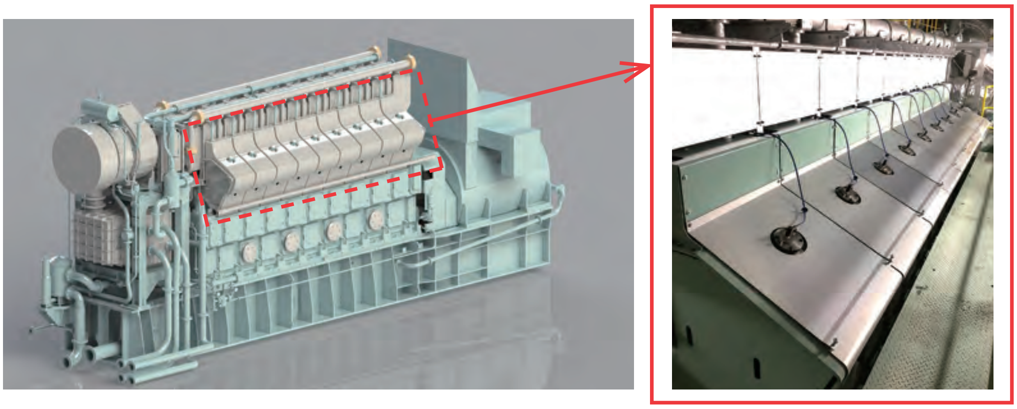

Fig. 2 Hydrogen mixed-fuel combustion gas engine for demonstration and leak detection covers

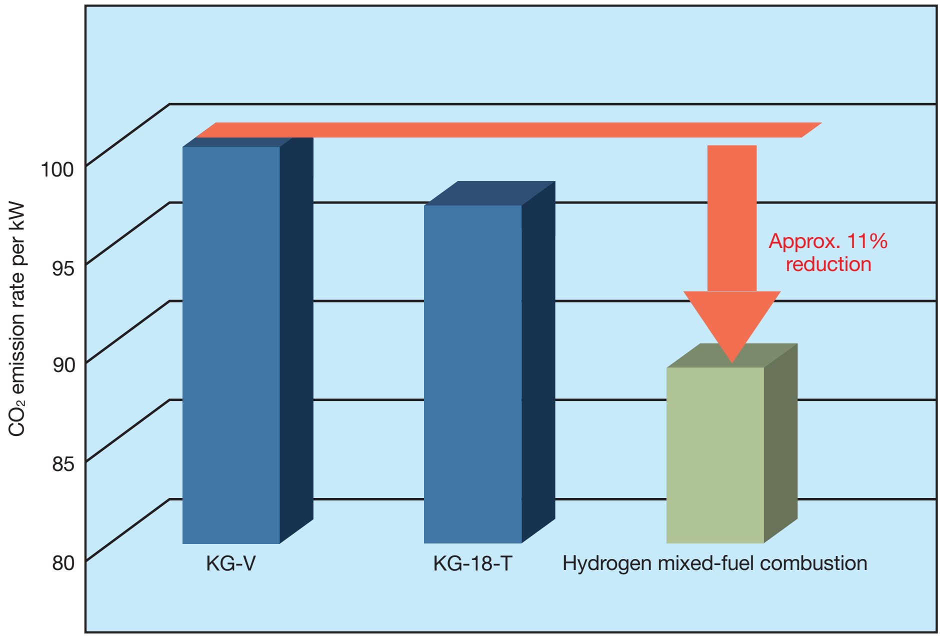

Fig. 3 Comparison of CO_2 emission rates among Kawasaki's gas engines

After conducting various tests on the demonstration unit, we plan to commercialize a model for hydrogen mixed-fuel combustion in 2025 and a model capable of 100% hydrogen combustion in addition to hydrogen mixed-fuel combustion in 2030. As shown in **Fig. 3**, 30% hydrogen mixed-fuel combustion reduces the CO_2 emission rate by about 11% compared to that of the conventional models, and 100% hydrogen combustion results in a 0% CO_2 emission rate.

Conclusion

Gas engines have been further developed to reduce CO_2 emission rates, and they will respond flexibly to the period of transition from a low-carbon society to a decarbonized society.

There are high expectations for this product, which incorporates technologies that contribute to the decarbonization of society, as we work toward the realization of a carbon neutral society in 2050.

Hiroshi Sato

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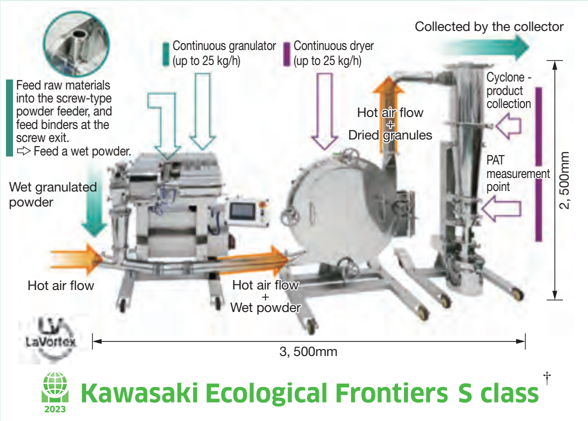
Continuous Granulation and Drying System for Pharmaceutical Powder LaVortex



The majority of solid pharmaceutical preparations (tablets and granules) are still manufactured using batch methods. However, the introduction of continuous production methods is being considered because of the advancement of sensor technology and government policies. We have developed LaVortex, a continuous manufacturing system capable of continuous granulation and drying of pharmaceutical powders. This system consists of LaVortex G, a continuous tube-rotating agitation granulator, and LaVortex D, a continuous air flow dryer. Compared to the conventional batch agitation granulation method and the fluidized bed granulation method, our system can continuously produce granules with properties superior for tablet compression, thereby facilitating mass production.

Introduction

In 2014, the U.S. FDA (Food and Drug Administration) published the ICH Q13 guidance for transitioning pharmaceutical production from conventional batch processing to continuous production processing. In Japan, the Pharmaceuticals and Medical Devices Agency (PMDA) has also announced a policy that encourages transitioning to continuous production. In conjunction with the advancement of sensor technology and government policies, this has led pharmaceutical manufacturers to consider introducing continuous production.

1 Background

The majority of solid pharmaceutical preparations (tablets and granules) are manufactured using batch methods, by which raw materials are fed into and discharged from equipment all at once, but their production efficiency is improving more slowly than methods in other industries. This is because with respect to production methods in which raw materials are continuously fed to continuously produce products, it is difficult to enforce conformity to the strict quality control standards applied to pharmaceuticals. To meet these standards, it is necessary to implement technology for constantly monitoring and controlling a continuous flow of raw materials and products throughout the process; such technology is referred to as a high-precision Process Analytical Technology (PAT). In continuous production methods, the manufacturing volume can be adjusted by changing the duration of operation. Other advantages include eliminating the need for scale-up considerations when transitioning from the development phase to the commercial production phase.

To facilitate continuous processing, we have developed LaVortex, a continuous production system for granulation and drying, which are the most important steps for manufacturing solid pharmaceutical preparations.

2 Product overview

As shown in the diagram, the continuous production system LaVortex consists of the continuous granulator LaVortex G and the continuous dryer LaVortex D, which together carry out the continuous granulation and drying of powder as well as produce dried granules from raw material powders and liquid binders. LaVortex supports a wide range of throughput rates for standard pharmaceutical prescriptions, from 2 to 25 kg/h.

† A completely continuous pharmaceutical production system that replaces a traditional batch manufacturing system with a continuous production method in order to control production quantity according to demand, stabilize production, and implement advanced quality control.

A raw mixture of active ingredients and other additives is fed into LaVortex G as a wet powder by feeding liquid binders into the screw-type powder feeder. The wet granulated powder continuously falls into the hot air pipe immediately beneath LaVortex G, is transported by a hot air flow, fed into LaVortex D, passes through the continuous drying unit while being dried, and then is collected by the cyclone. The PAT equipment installed in the lower part of the cyclone continuously measures the moisture content and diameter of the dried granules. The diverter valve operates in accordance with the quality determined from the measurement results, transporting only conforming granules to the next process.

3 Product features

(1) Features of the continuous granulator LaVortex G

The structure of LaVortex G's continuous granulation unit is shown in **Fig. 1**. It adopts the tube-rotating agitation method, which makes use of our expertise in batch agitation granulators. The chopper blades and the rotation tube rotate in the same direction. The high-speed rotation of the chopper blades and the low-speed rotation of the rotation tube facilitate granulation. A wet mixture of raw powders and liquid binders is fed into the feeding port, transported to the continuous granulation unit by the screw, and agitated by the rotation of the chopper blades and the rotation tube with their axes of rotation being offset from each other. In the lower part of the continuous granulation unit, the chopper blades are positioned closely to the rotation tube so that the chopper blades are structurally more likely to make contact with the wet powder moving near the wall of the rotation tube. By contrast, in the upper part, the two partition plates separate the continuous granulation unit so that the wet powder stays longer. In addition, the chopper shaft also has two disks, not blades, at positions near the aforementioned partition plates. Combined, these help the wet powder stay longer in the continuous granulation unit while sizing it. The wet granulated powder that passes through the continuous granulation unit is continuously discharged from the discharging port and transported to the next step.

(2) Features of the continuous dryer LaVortex D

LaVortex D consists of a two-layered spiral drying chamber. The structure of its continuous drying unit is shown in **Fig. 2**. The wet granulated powder discharged from LaVortex G is transported by a hot air flow, dried while passing through the 10-meter-long continuous

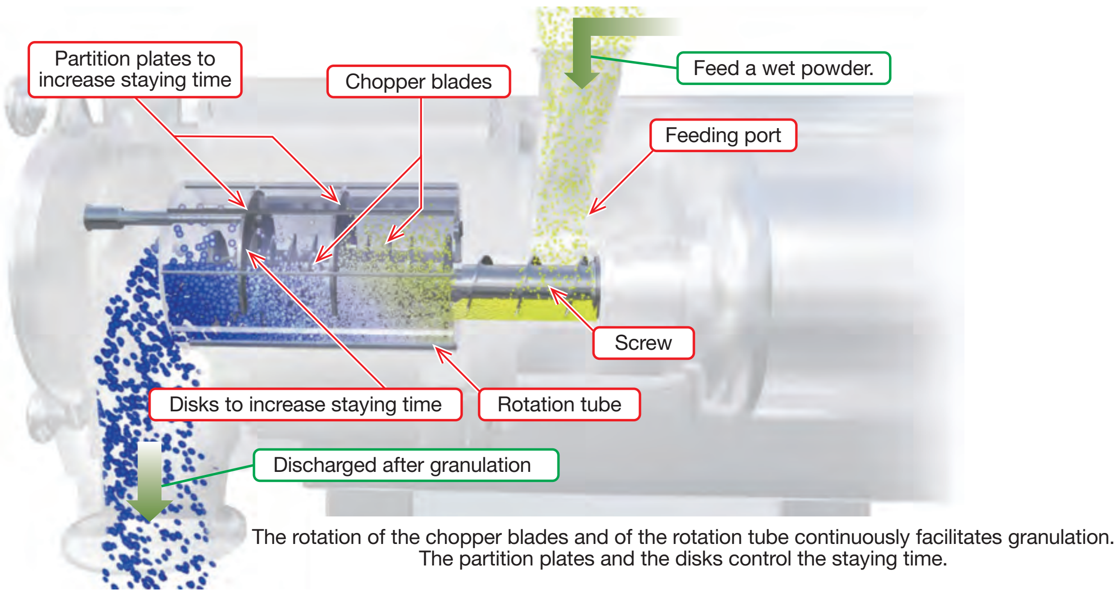
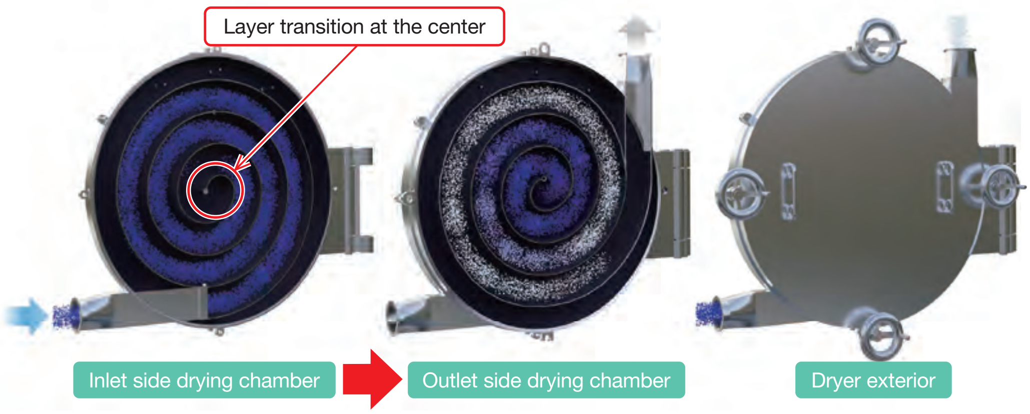


Fig. 1 Structure of continuous granulation unit



To divide the unit into two layers, there is an intermediate plate between the inlet side and outlet side drying chambers.

Fig. 2 Structure of continuous drying unit

drying unit, and collected by the cyclone. The drying unit is divided into two layers, namely the inlet side drying chamber and the outlet side drying chamber, which face each other across an intermediate plate. A spiral-shaped plate is affixed in each drying chamber to create a two-layered spiral air flow channel. The hot air flow and wet granulated powder flowing from the hot air pipe enter the periphery of the inlet side drying chamber and pass through the channel that leads to the center of the spiral. After reaching the center of the spiral, they proceed to the outlet side drying chamber through the hole in the intermediate plate and then pass through the channel that leads outwards from the center of the spiral. This realizes a structure that makes the walls of the drying channel, which contact with the outside, small in area and reduces radiation loss. After reaching the outermost periphery, the dried granules are discharged from the continuous drying unit and then collected by the cyclone.

The dried granules are continuously measured by the PAT equipment installed in the lower part of the cyclone. As the PAT equipment, a near infrared spectroscopy and a particulate probe capable of nondestructive measurement are installed to measure the moisture content, particle diameter, and particle size distribution in real time. To precisely measure the moisture content using near infrared spectroscopy, dried granules are temporarily accumulated by the diverter valve and semicontinuously measured in small quantities. The diameter is measured completely continuously without accumulating the granules by means of a measurement nozzle installed in the cyclone channel. This measurement confirms that the granules produced by LaVortex are of uniform quality.

(3) Comparison with conventional granulation methods

Table 1 shows a comparison between the granulation and drying method employed for LaVortex and conventional batch methods, namely agitation granulation and fluidized bed granulation, under the condition that the processing volume is 25 kg/h. The particle size distribution breadth and bulk density of granules produced by LaVortex fall between those of granules produced using

Table 1 Comparison with conventional granulation methods

Granulation method	① 「LaVortex」	② Agitation granulation	③ Fluidized bed granulation
Production method	Continuous	Batch	Batch
Particle diameter d10 〔μm〕	58. 4	62. 9	62. 2
Particle diameter d50 〔μm〕	181. 0	197. 9	125. 1
Particle diameter d90 〔μm〕	537. 8	670. 3	234. 2
Particle size distribution breadth	Medium	Broad	Narrow
Bulk density 〔g/mL〕	0. 547 medium	0. 730 high	0. 390 low
Tablet hardness 〔N〕	70 appropriate	35 low	75 appropriate

Fig. 3 Granular shape and surface condition

conventional methods. In addition, LaVortex produces granules that are spherical and easy to process, like those produced using the agitation granulation method, as shown in **Fig. 3** while exhibiting appropriate tablet hardness (the force required to break a formed tablet), like those produced using the fluidized bed granulation method. Thus, LaVortex can continuously mass-produce granules with excellent tablet hardness that can easily be formed into tablets.

Conclusion

We are currently promoting LaVortex not only in the pharmaceutical industry but in the food and chemical industries. We are also developing a continuous manufacturing system for mixing pre-granulated raw materials for the stages preceding and succeeding granulation and drying.

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Eco-friendly Hybrid and Battery Propulsion and Power Supply Systems for Coastal Vessels

Kawasaki Ecological Frontiers S class†

Reducing greenhouse gas (GHG) emissions is an urgent challenge to mitigate global warming, and to this end, the development of ships with excellent environmental performance is required. As a system integrator, we have developed hybrid propulsion and power supply systems as well as battery propulsion and power supply systems that utilize our proprietary gas engines, thereby significantly improving the environmental performance of ships.

Introduction

Reducing greenhouse gas (GHG) emissions is an urgent challenge to mitigate global warming. As environmental restrictions have been tightened in the marine industry as well, the development of ships with excellent environmental performance is required.

1 Background

In July 2023, the International Maritime Organization (IMO) adopted GHG reduction strategies for the international maritime industry. The IMO aims to achieve net zero GHG emissions by around 2050 and has set gradual reduction goals to do so.

Momentum for GHG emissions restrictions is also increasing in Japan, and the Ministry of Land, Infrastructure, Transport and Tourism raised the goal for reducing CO_2 emissions attributable to non-international coastal trading from 15% to 17% by FY2030 compared to FY2013.

Though individual pieces of equipment have been improved in conventional ships, such as enhanced hull forms and improved engine and propeller performance, further performance improvements are now required to respond to these rising social needs.

To attain this ambitious goal, we decided to achieve optimization by considering the amount of necessary energy for each ship as a whole. We have developed two systems in order to propose the optimal configurations according to ship operations and cruising distances.

2 Hybrid propulsion and power supply system

The system shown in **Fig. 1** is suitable for long cruising distances as it electrically couples the main engine, which serves as the propulsion power source, and the generator, which functions as the onboard power supply, to achieve optimal supply for ship operations so as to realize energy-efficient operation. This system has the following features.

① High environmental performance achieved in combination with a pure LNG engine

The combination of our proprietary pure LNG engine, Kawasaki Green Gas Engine L30KG (**Fig. 2**), and a battery achieves high environmental performance.

② Improvement of fuel economy

The fuel economy of ships drops when engine loads fluctuate due to climate and hydrographic conditions. By using the battery to limit the impact of this load fluctuation on the engine, we can significantly improve fuel economy, especially in rough weather.

③ Zero emissions in ports

In situations in which the required propulsion power is small, such as in ports, the system enables zero-emissions travel when powered solely by the battery.

† A system that switches between multiple energy sources depending on ship operations in order to maximize efficiency and to reduce exhaust gases. For example, this system can achieve zero emissions with electrical propulsion using the battery when entering and leaving ports and use mechanical propulsion for efficient propulsion while cruising.

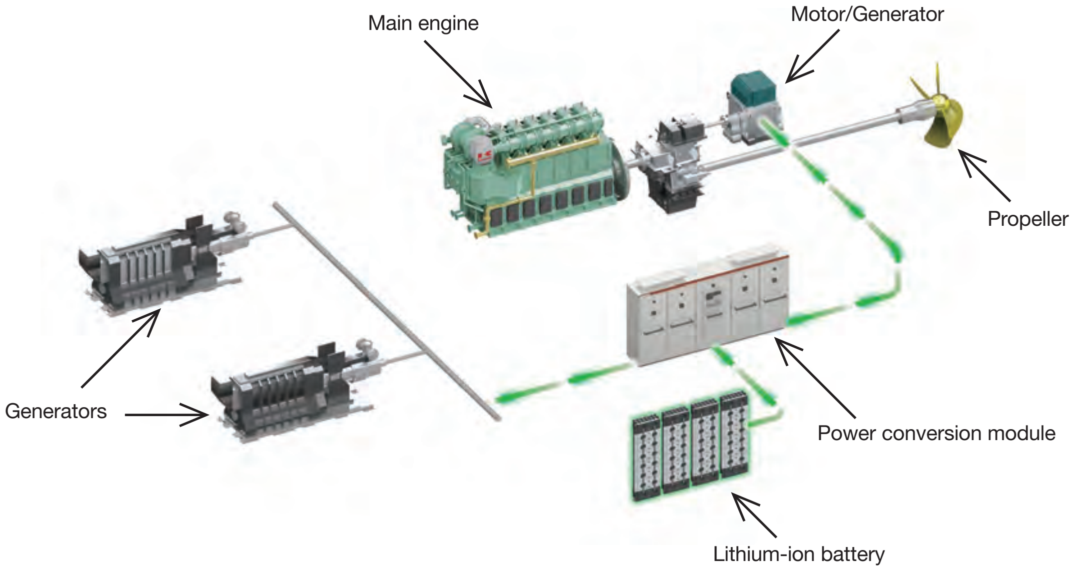

Fig. 1 Hybrid propulsion and power supply system

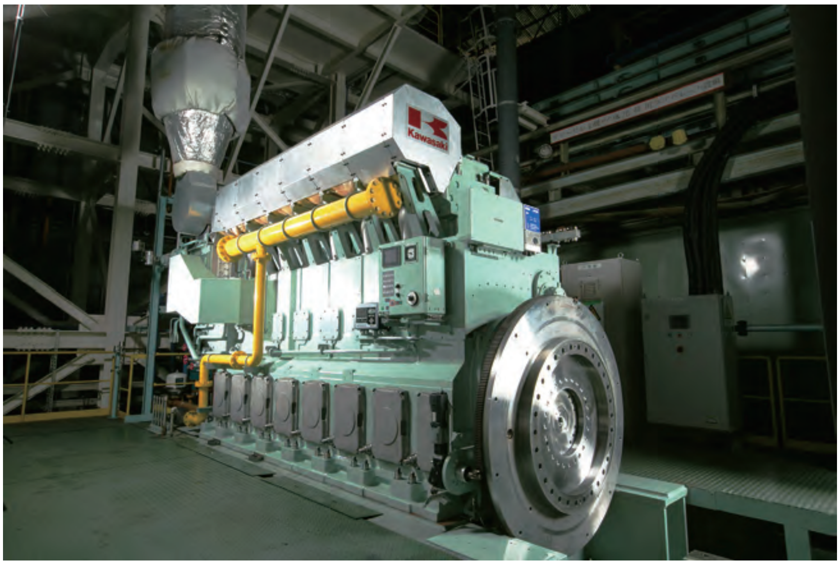

Fig. 2 Kawasaki Green Gas Engine L30KG

④ Safety enhancement

Even if the engine is inoperable, the ship can continue navigation with battery power.

3 Battery propulsion and power supply system

The fully battery-powered system is suitable for short cruising distances. This system has the following features.

① Zero emissions

The ship does not emit any GHG during operation.

② Reduction in vibration and noise

Free of engine vibration and noise, the ship does not cause a nuisance to the crew or people living near ports.

③ Power supply to land in disasters

The ship can supply electricity stored in its battery to land as an emergency power supply in the event of a natural disaster.

④ Crew workload reduction

Crew workloads are significantly reduced because the ship does not require a warming-up operation or main engine maintenance.

4 Delivery and implementation cases

To make the most of the features of each system, appropriate equipment and a system configuration must be selected according to the application and cruising distance of the ship. We can propose the optimal propulsion and power supply system for ship operations by leveraging our rich experience accumulated over many years as a marine equipment manufacturer.

(1) Limestone carrier

We have received an order for the gas engine hybrid propulsion and power supply system to be installed on a limestone carrier that NS United Naiko Kaiun Kaisha, Ltd. plans to operate. The system properly controls the gas engine, motor/generator, and 2.8-MWh large-capacity battery to achieve optimal operation for GHG emissions reduction. The carrier can reduce CO_2 emissions by about 30%, NOx emissions by about 90%, and SOx emissions by about 100% compared to conventional carriers of the same type at normal output, and it reduces methane slip. In other words, this is a very environmentally friendly carrier. The carrier is planned to be completed in 2024.

(2) The world's first pure battery tankers, Asahi and Akari

The world's first pure battery tanker incorporating our battery propulsion and power supply system, Asahi, was completed in March 2022 (**Fig. 3**). This carrier, which was

Fig. 3 Pure battery tanker Asahi
(Source: Asahi Tanker Co., Ltd.)

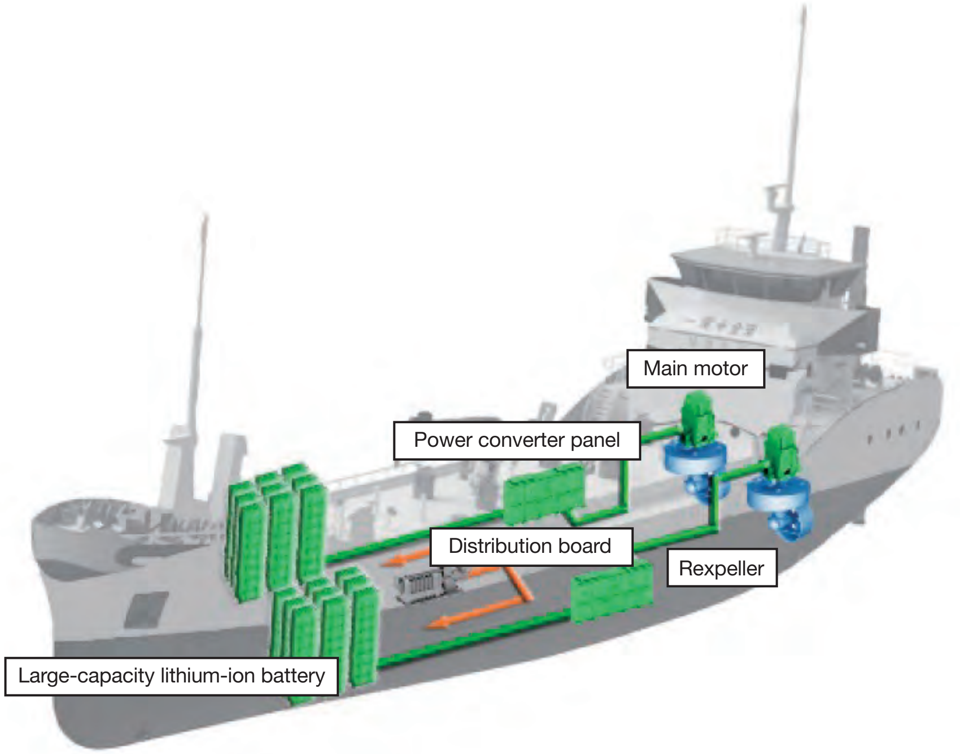

Fig. 4 Installation of main components

ordered by Asahi Tanker Co., Ltd., achieves zero emissions during operation by using electricity stored in a 3.5-MWh large-capacity battery for propulsion and power supply. **Fig. 4** shows the installation of the main components, which we were in charge of. Its sister ship that employs the same system, Akari, was completed in March 2023, and both are now used to supply marine fuel in Tokyo Bay.

Conclusion

We will continue to contribute to improving the global environment, aiming to popularize environmentally-friendly ships that employ this system.

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An 86,700 m^3 LPG-fueled LPG/NH_3 Carrier

Kawasaki Ecological Frontiers S class†

This LPG/NH_3 carrier can transport LPG, which is widely used as an energy source with low environmental impact, and ammonia, which is expected to be used as a new fuel in the carbon neutral society of the future. This carrier can use LPG as the main engine fuel. While maintaining the main dimensions of the conventional LPG carrier built in our shipyard, it features a larger cargo tank capacity and achieves the world's lowest level of fuel consumption.

Introduction

As one of the world's largest energy consumers, Japan has used LPG as clean energy in a wide range of areas, such as general households, taxies and industry. Very Large Gas Carriers (VLGC) that transport LPG are essential for Japan because most of LPG used in Japan is imported.

1 Background

Competition for orders is vigorous as an increasing number of VLGCs are being constructed not only in Japan but in Korea and China as well. In addition, to boost transportation efficiency, the VLGC becomes larger. As market trends are changing, we had to develop a new VLGC that customers like better than those of our competitors as quickly as possible.

We also reviewed the specifications for transporting ammonia, which has recently been gathering attention as a CO_2-free fuel.

2 Overview and features

Table 1 shows the principal particulars of this carrier, while **Fig. 1** shows the general arrangement. This carrier has the largest hull dimensions satisfied to main LPG terminals in Japan.

The carrier has three new features, namely lower fuel consumption than that of conventional ships, an enlarged cargo tank, and ammonia transportation capability. It also supports LPG fuel, which is more environmentally friendly than fuel oil.

(1) Low fuel consumption

We have improved the hull form to achieve best-ever propulsion performance by leveraging sea trial data we have accumulated. We also adopted newly developed energy-saving fins (short horizontal fins) (**Fig. 2 (d)**) in addition to our proprietary SEA-Arrow hull form (**Fig. 2 (a)**) and energy-saving devices (semi duct system with contra fins, rudder bulb system with fins) (**Fig. 2 (b)** and **(c)**) that we have adopted in conventional ships. We achieved the world's best fuel consumption level, improving fuel consumption by about 6% from the previous series of 84,000 m^3 LPG-fueled LPG carriers by adopting a fuel-efficient main engine, in addition to the hull form improvement and energy-saving devices.

(2) Increase of cargo tank capacity

Many LPG terminals were designed in accordance with LPG hull dimensions that were available at the time when such terminals were constructed, and they are no longer optimal for today's larger hull dimensions. Therefore, if ship size is increased without careful

† A large LPG carrier that achieves significant reduction in environmental impact by using LPG as its main fuel through adoption of the ME-LGIP dual-fuel slow-speed diesel engine that can switch between LPG and fuel oil.

Table 1 Principal particulars

Ship type	Heavy oil/LPG dual fuel propulsion LPG/NH_3 carrier
Length overall × width × form depth [m]	Abt. 230×37. 2×21. 9
Cargo capacity [m^3]	86, 700
Service speed [knots]	17

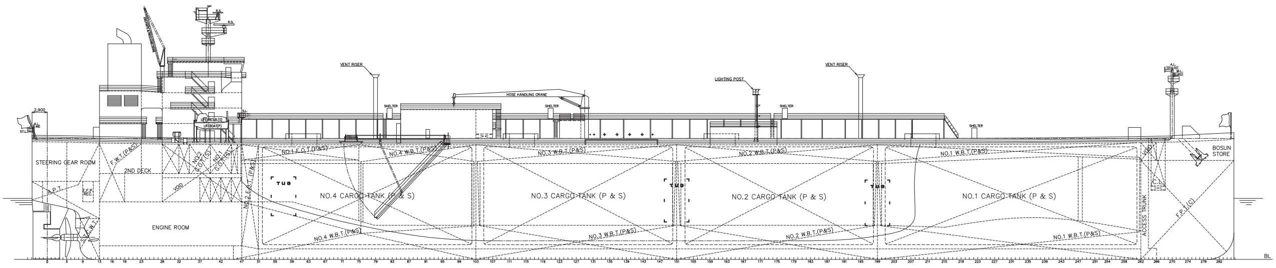
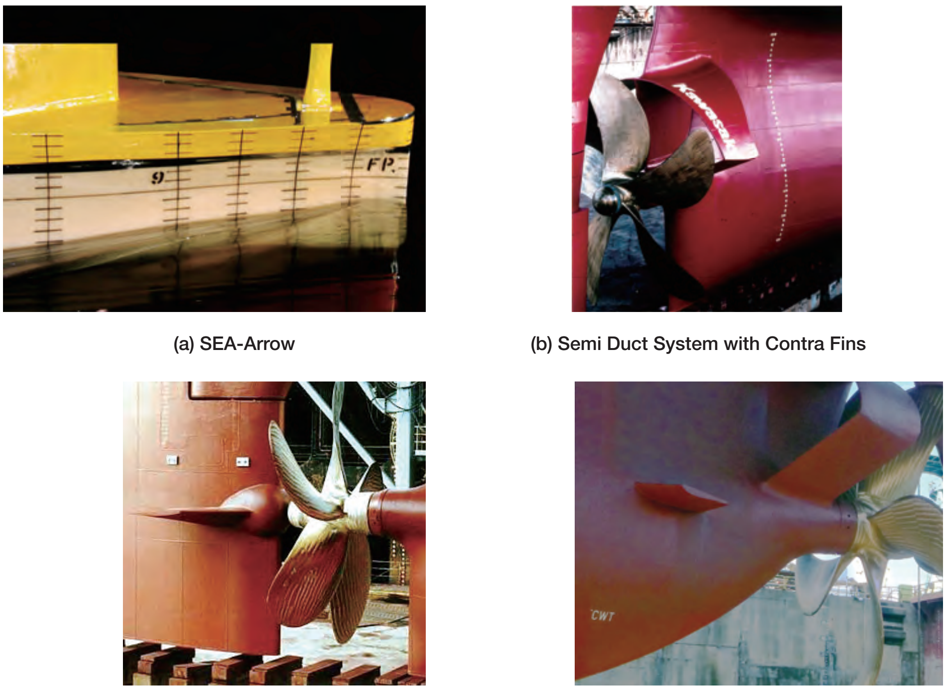


Fig. 1 General arrangement



(a) SEA-Arrow

(b) Semi Duct System with Contra Fins

(c) Rudder Buib System with Fins

(d) Short Horizontal Fins

Fig. 2 Bow form and energy-saving devices consideration, the resulting ship will encounter challenges. For example, the ship may not be allowed to land to important terminals or entry may be limited. Therefore, we decided to increase the cargo tank capacity without changing the main dimensions, based on which terminals may apply restrictions, so that the new carrier can continue to enter the same terminals as the previous series of 84,000 m^3 LPG carriers.

The cargo tank has the capacity to load an amount of LPG fuel sufficient for a round trip between Huston and the Far East and provides sufficient cargo capacity. The route between Huston and the Far East is one of the main routes. In addition, although LPG is often traded in lots based on cargo weight, the value has been changing over the decades. So, we have ensured a cargo capacity sufficient for the latest transaction lots.

(3) Support for ammonia transportation

We changed the specifications to load ammonia, which has recently been gathering attention as a CO_2-free fuel. We placed particular focus on corrosiveness, specific gravity, and operation.

Because ammonia may cause stress corrosion cracking of some materials, we changed the material to one that is resistant to it.

In addition, because ammonia in a liquid state has a higher specific gravity than LPG, we changed the specifications of the cargo equipment to handle this higher specific gravity. Furthermore, because ammonia in a gas state is lighter than air, unlike LPG, we installed safe equipment in the upper part of the area such as a cargo machinery room, in addition to the lower part of the area where the equipment is already installed for LPG.

For the operation of ammonia, we prepared necessary equipment according to our experience with the multi gas carrier we constructed about 20 years ago and various guidelines.

We not only changed the specifications to transport ammonia as cargo but partially acquired the ammonia fuel ready notation, a class that enables us to use ammonia as fuel for the main engine in the future, to further reduce CO_2 emissions.

(4) LPG fuel supply system

Since we constructed the first LPG fuel LPG carrier in Japan, the LPG fuel system has been the global standard for LPG carriers. We led the world in starting development of an LPG fuel system, in consideration of environmental impact, and we developed a proprietary LPG fuel supply system based on our knowledge of LPG carriers accumulated over the years and the LNG fuel systems we have already developed and implemented.

Fig. 3 shows an outline drawing of the LPG fuel supply system. The main features are the presence of a service tank and individual control of each line.

The service tank stores the minimum necessary amount of LPG to be used as fuel. In addition, the service tank prevents the cargo contamination if lubrication oil

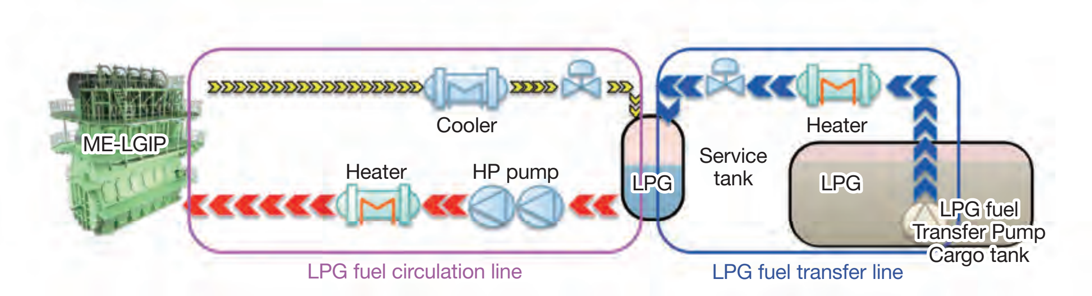


Fig. 3　LPG fuel supply system diagram

enters the cargo tank, as LPG returning from the main engine is contaminated with a small amount of lubrication oil. We developed the fuel supply system around the service tank to realize a simple control mechanism to individually control the fuel transfer line and the fuel circulation line.

We developed a control system for each line, repeating simulations with assumed temperatures and physical properties. We constructed a simple system that monitors LPG within the system to prevent it from boiling and maintains it in a liquid state with appropriate control equipment because LPG in a liquid state is supplied to the whole system.

Conclusion

This carrier has become a huge success compared to previous ships and is highly appreciated by many shipowners.

In order to contribute to the realization of a low-carbon and carbon neutral society, we will develop and provide environmentally friendly ship technologies starting with the 86,700 m^3 LPG/NH_3 carrier shown in the top photo in light of environmental restrictions, which are increasingly tightening around the world, and specific action plans as exemplified by the SDGs.

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Kawasaki Heavy Industries Group
Main Products and Production Bases by Business Segment

Business Segment	Main Products	Main Production Bases
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.)
Aerospace Systems	• Aircraft components, rocket components, space equipment, target systems • Aircraft servicing, remodeling	NIPPI Corporation • Yokohama Plant (Yokohama, Kanagawa Prefecture) • Atsugi Plant (Yamato, Kanagawa Prefecture)
Aerospace Systems	• Aircraft engines • Aircraft gear boxes	Akashi Works (Akashi, Hyogo Prefecture) Seishin Works (Kobe, Hyogo Prefecture)
Rolling Stock (Kawasaki Railcar Manufacturing Co., Ltd.)	• Train cars, integrated transit systems	Head Office & 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.)
Rolling Stock (Kawasaki Railcar Manufacturing Co., Ltd.)	• Rotary snowplows, deicing material spreaders • Railway motor cars, heavy-lift cars	NICHIJO CORPORATION. • Akebono Plant (Sapporo, Hokkaido) • Inaho Plant (Sapporo, Hokkaido)
Energy Solution & Marine 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	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)*
Energy Solution & Marine Engineering	• Industrial gas turbines, marine gas turbines	Akashi Works (Akashi, Hyogo Prefecture) Kobe Works (Kobe, Hyogo Prefecture)
Energy Solution & Marine Engineering	• 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)
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Energy Solution & Marine Engineering	• Crushers, recycling equipment and plant	EARTHTECHNICA Co., Ltd. • Yachiyo Works (Yachiyo, Chiba Prefecture)
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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)
Precision Machinery & Robot	• Hydraulic presses	Kawasaki Hydromechanics Corporation (Akashi, Hyogo Prefecture)
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Kawasaki Ecological Frontiers

Since 2014 the Kawasaki Group has implemented its Kawasaki Ecological Frontiers system (formerly Kawasaki-brand Green Products system), an internal system for certifying environmentally friendly products, as a means of reducing the environmental burden of the Group's products and services throughout their life cycles. Under the system, superior products—in terms of whether the products themselves evidence improved environmental performance and whether the associated manufacturing processes demonstrate a reduced environmental impact—are certified and registered.

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