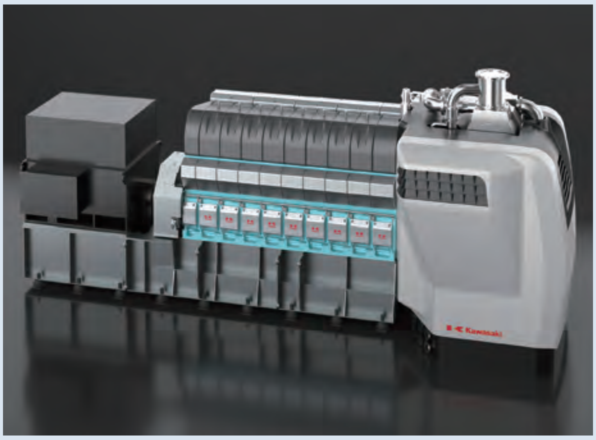
Development of Marine Hydrogen Dual Fuel Engine and Marine Hydrogen Fuel System Promotes a Carbon Neutral Society



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

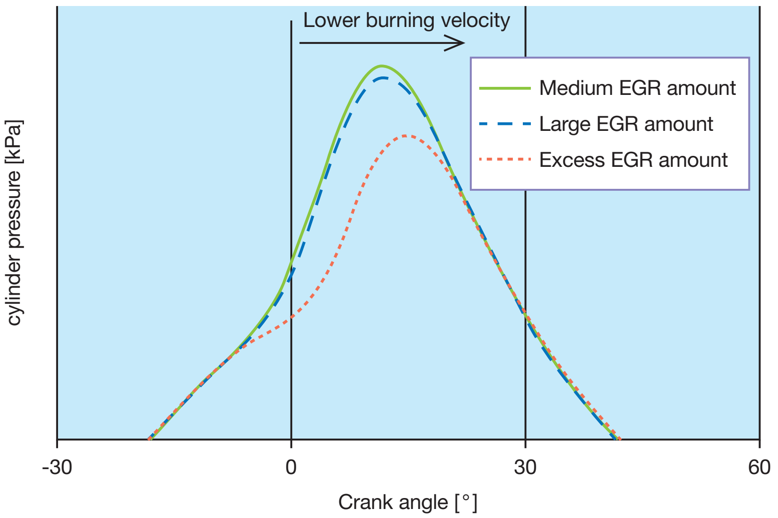


Fig. 1 Differences in peak cylinder pressure by EGR amount

(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

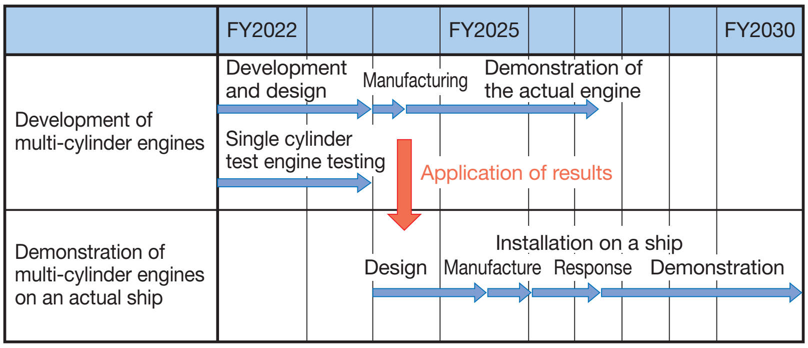
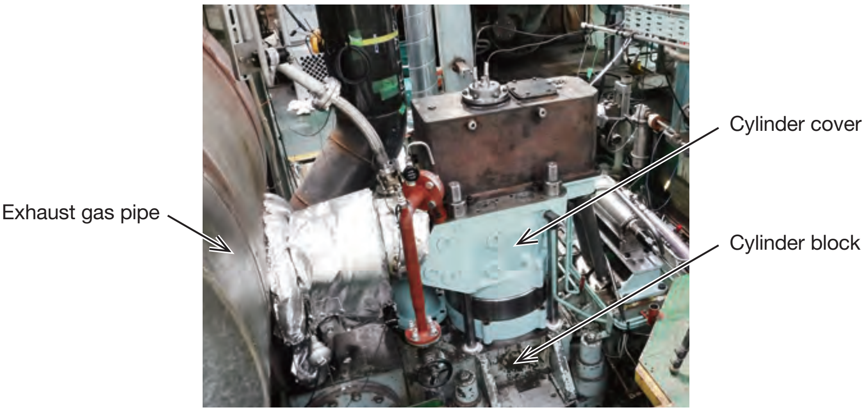


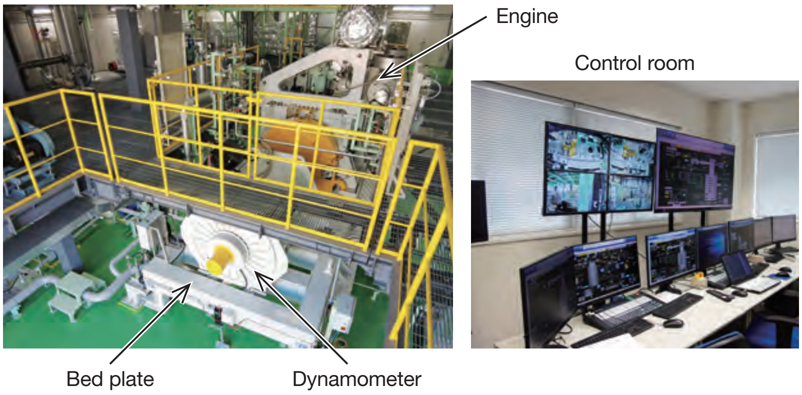
Fig. 2 Overall development schedule

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

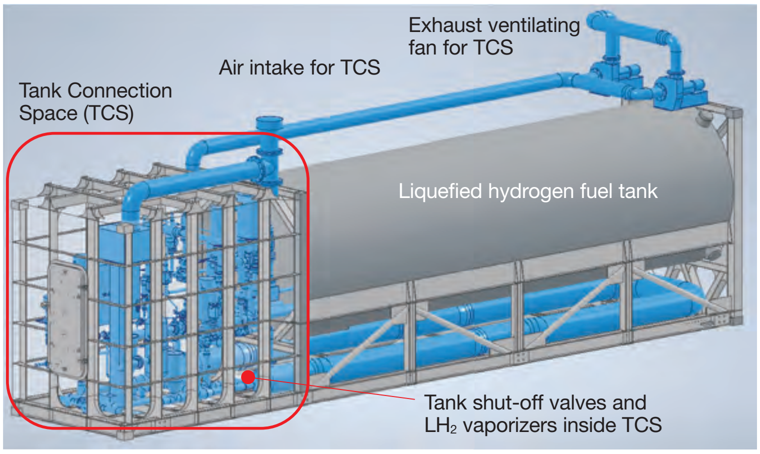


Fig. 4 General view of MHFS unit (for four-stroke engine)

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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