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# Realization of decarbonization through development of marine hydrogen dual fuel engine

New Engine Concepts & Systems

Masato Nakai, Kawasaki Heavy Industries, Ltd.

## ABSTRACT

Kawasaki Heavy Industries is developing a 4-stroke hydrogen engine to realize decarbonization from ships. This engine is a dual fuel engine that can be operated with both hydrogen and liquid fuels to satisfy the requirement of marine redundancy. In addition, a premixing system by port injection was adopted, and auxiliary power was minimized by applying low-pressure hydrogen gas, and high output per cylinder was realized by optimizing combustion. This paper introduces the technical features of this engine.

First of all, there is a problem that it is difficult to increase the output per cylinder because hydrogen tends to cause abnormal combustion compared with existing fuel oil and natural gas. In order to solve this problem, combustion evaluation using a single-cylinder test engine was carried out. In particular, high output using hydrogen fuel was realized by combustion optimization utilizing an exhaust gas recirculation system (EGR). In the multi-cylinder engine, CFD and dynamic simulation were repeated based on the basic research by the single-cylinder test engine, and the turbocharger and EGR were made compact and modular. It was completed as a flexible engine capable of operating liquid fuel on the basis of hydrogen combustion with variable valve equipment aiming at compatibility with liquid fuel. The control system also enables switching between hydrogen fuel and liquid fuel, enabling stable and continuous operation.

It is necessary to evaluate the effect of hydrogen embrittlement, because hydrogen has the property of degrading material strength by hydrogen embrittlement. The SSRT test and the fatigue test were carried out to investigate the hydrogen embrittlement of each member, and the materials to be applied were selected.

The design and manufacture of the multi-cylinder engine reflecting the above study results were completed, and shop tests were started. In the future, performance and functional tests will be conducted on the developed engine. In addition, long-term reliability will be confirmed by actual ship demonstration, and commercialization will be targeted around 2030 to realize decarbonization.

# 1 INTRODUCTION

Since the entry into force of the Paris Agreement, awareness has shifted from a low-carbon society to a decarbonized society. Decarbonization is required in the energy and shipping fields. In Japan, CO2 reduction targets are set at 46% of the 2013 level by 2030 and carbon neutrality by 2050. GHG reduction targets for international shipping are shown in Figure 1. The "2023 IMO GHG Reduction Strategy" was adopted at IMO MEPC 80 and the GHG reduction target was brought forward. It is internationally agreed that “Reduce GHG emissions by 20~30% by 2030, reduce GHG emissions by 70~80% by 2040 (relative to 2008), and aim for 0 GHG emissions by around 2050.”

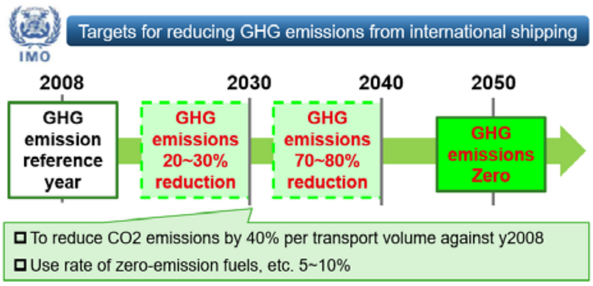


Figure 1 IMO GHG reduction targets

Under these circumstances, the market for marine hydrogen engines using hydrogen as decarbonized fuel is expected to expand rapidly toward the decarbonization of the shipping industry. Accordingly, equipment to supply hydrogen fuel gas stably and safely on ships is required.

Kawasaki Heavy Industries, Ltd. is developing a 4-stroke hydrogen gas engine to realize decarbonization from ships. A photograph of the engine under development is shown in Figure 2. The initial development of this engine using a single-cylinder test engine has been completed, and the design and shop test of a multi-cylinder engine have started. This paper introduces the development status of this engine, focusing on its technical features.

Figure 2 A picture of the development engine

# 2 STRUCTURE OF HYDROGEN GAS ENGINE

The engine was developed based on the marine natural gas engine owned by our company. The main specifications of the newly developed demonstration engine are shown in Table 1. Figure 3 shows an image of the combustion chamber.

Table 1 Main specifications of the development engine

| Item | | Main specifications |
|---|---|---|
| Bore | | 300 mm |
| Stroke | | 480 mm |
| Speed | | 720 min-1 |
| No.of cylindre | | 8 |
| BMEP | H mode | 1.60 kPa |
| | D mode | 1.95 MPa |
| Pressure of hydrogen | | < 1.0 MPa |
| Shaft end Output | H mode | 2600 kW |
| | D mode | 3200 kW |
| Fuel (Calorific value) | H mode | Hydrogen 95% Pilot oil (LS MGO) 5% |
| | D mode | LS-MGO 100% |

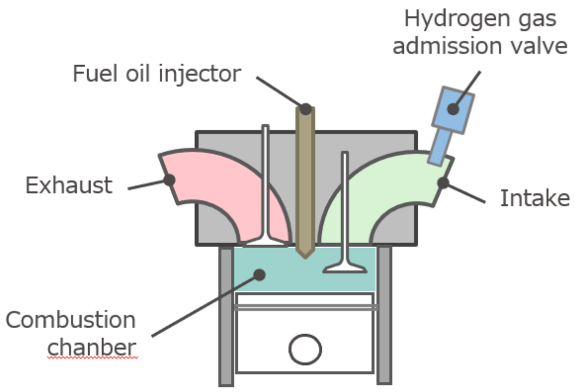


Figure 3 Image of Combustion Chamber

Cylinder diameter and stroke follow the base engine. An 8 cylinder engine will be produced for demonstration purposes, but larger engines such as 12 V and 18 V are also considered for future line-up. In order to cope with the redundancy of marine engines, a pilot ignition dual-fuel engine is adopted, and diesel operation using fuel oil (D-mode operation) and hydrogen operation using hydrogen gas (H-mode operation) are possible. In the H-mode operation, fuel oil equivalent to 5% of the total heat input is used for pilot ignition, and hydrogen gas input amount is more than 95% of the total fuel input amount. The net mean effective pressure is

1.60 MPa, which is unparalleled in the engine size of this class.

Hydrogen gas is supplied to the intake port at a low pressure of less than 1 MPa, and a premixed combustion system is adopted in which hydrogen gas is supplied to the combustion chamber while mixing air and hydrogen. Since the supply pressure of hydrogen is low, the auxiliary power accompanying the pressure rise of hydrogen can be reduced.

The fuel oil is supplied directly from the fuel oil injection valve into the combustion chamber using a common rail system. The injection timing, injection quantity, and number of injection can be controlled by electronic control.

In summary, the features of this development engine are as follows.

- ✓ Dual-Fuel engines with a hydrogen co-firing ratio of 95% or more
- ✓ High BMEP for the equivalent engine size
- ✓ Low hydrogen supply pressure due to use of premixing system

## 3 TECHNICAL ISSUE WITH HYDROGEN GAS ENGINES

Hydrogen has the following characteristics with respect to methane, the main component of natural gas, depending on the difference in physical properties.

Hydrogen has a smaller molecular weight than methane and is easy to leak. Therefore, it is generally known that welded joints should be used for hydrogen piping as much as possible and flange joints should be avoided as much as possible.

Since hydrogen has a low calorific value relative to methane, the volume flow rate of the fuel increases, and the compression power required for boosting the hydrogen gas increases. The development engine adopts the premixed combustion system which can supply hydrogen at low pressure in order to minimize the compression power.

Since hydrogen has a wide combustible range against methane, the concentration in the engine combustion chamber of a hydrogen gas engine is considerably higher than the lower explosion limit. Therefore, it is easy to ignite and cause abnormal combustion. In addition, the hydrogen concentration of the blow-by gas leaking from the engine combustion chamber into the crankcase increases, and a hydrogen explosion in the crankcase is feared.

Hydrogen has a very small minimum ignition energy compared to methane. The high-temperature part in the engine combustion chamber becomes an ignition source, and hydrogen ignites at an unintended timing, causing abnormal combustion. The largest problem of hydrogen gas engine development is this abnormal combustion.

Hydrogen is known to charge into metallic materials and cause hydrogen embrittlement which reduces their mechanical properties. In developing a hydrogen gas engine, it is necessary to investigate the reliability due to the effect of hydrogen embrittlement.

The technical issues of this development engine are as follows.

- ✓ Prone to abnormal combustion
- ✓ Concern of hydrogen explosion in crankcase
- ✓ Loss of reliability due to hydrogen embrittlement

## 4 DEVELOPMENT OF HYDROGEN GAS ENGINE

### 4.1 Measures against abnormal combustion

As mentioned in Section 3, the biggest problem in developing hydrogen gas engines is abnormal combustion. This section describes countermeasures against abnormal combustion of the hydrogen gas engine.

Hydrogen is more likely to cause abnormal combustion than natural gas. Abnormal combustion can be suppressed by bringing the physical properties of hydrogen close to those of natural gas. Exhaust gas recirculation (EGR) is applied to this developed engine to return exhaust gas to intake air for abnormal combustion countermeasure. The oxygen concentration in the intake air was reduced by EGR, and the effect of abnormal combustion suppression of the hydrogen gas engine was confirmed. In order to confirm the effect of EGR, hydrogen combustion was evaluated using a single-cylinder test machine with the same main specifications as the actual machine shown in Figure 4. The results are shown in Figure 5.

Figure 4 A picture of a single-cylinder test engine

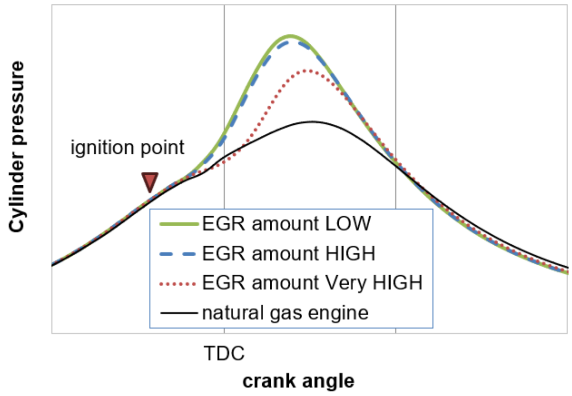


Figure 5 Results of combustion characteristics measurement by changing EGR rate

The EGR amount was used as a parameter, and all other conditions were the same. For reference, the combustion waveform is shown when the fuel is natural gas under the same conditions. Under the test conditions, the evaluation could not be performed without EGR due to abnormal combustion. Therefore, the test was started with EGR applied, and the amount of EGR was increased little by little. When the amount of EGR is small, the combustion speed is higher than that of the natural gas engine, so the cylinder pressure is very high. The pressure in the cylinder hardly decreased by increasing the amount of EGR. However, it was confirmed that there was a region in which the pressure in the cylinder decreased abruptly when the EGR amount was applied over a certain amount. This means that the combustion speed is reduced, which indicates that there is an abnormal combustion suppression effect. In hydrogen gas engine, abnormal combustion can be suppressed by applying large amount of EGR.

In addition to the EGR, the engine specifications were determined by optimizing the compression ratio and the timing of the intake and exhaust valves through tests using a single-cylinder test engine.

### 4.2 Measures against hydrogen explosion in crankcase

Since the concentration of the mixed gas in the combustion chamber of the hydrogen gas engine is higher than that of the natural gas engine, the hydrogen concentration in the crankcase may reach the explosion range due to the leakage of the blow-by gas from the combustion chamber, causing an explosion. In order to avoid this, the crankcase was actively ventilated. The amount of hydrogen leaked into the crankcase was measured in the single-cylinder test engine, and the required ventilation air volume was calculated by design calculation. It was also confirmed by CFD analysis that hydrogen did not remain in the crankcase. The CFD analysis results are shown in Figure 6.

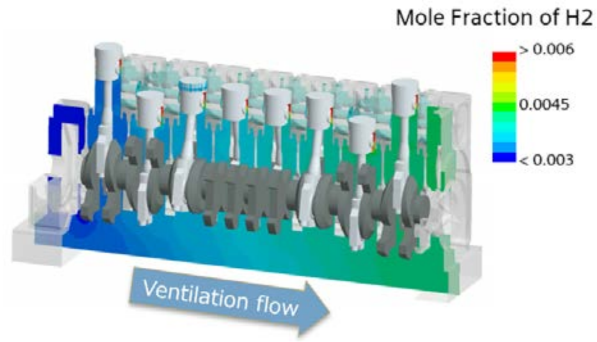


Figure 6 Crankcase Ventilation Analysis Results

As the blow-by gas leaks from each cylinder, it can be seen that the hydrogen concentration increases from the upstream to the downstream of the ventilation. The maximum hydrogen concentration was about 0.5%, and it was confirmed that there was no hydrogen retention point of flammable concentration. Based on the analysis results, the ventilation specification that does not cause the combustible concentration in the crankcase was determined.

### 4.3 Measures against hydrogen embrittlement

It is known that hydrogen penetrates into metallic materials and causes hydrogen embrittlement which reduces metal strength. The presence or absence of hydrogen embrittlement can be checked by AIAA(American Institute of Aeronautics and Astronautics). It is stated that cast iron used in the engine combustion chamber is hydrogen embrittled in 100% hydrogen environment. However, hydrogen concentration is not 100%

under actual engine operating environment. Therefore, it was confirmed whether there was no effect of hydrogen embrittlement under the engine operating environment. SSRT (Slow Strain Rate Technique) test was applied for confirmation. The outline of the test equipment is shown in Figure 7.

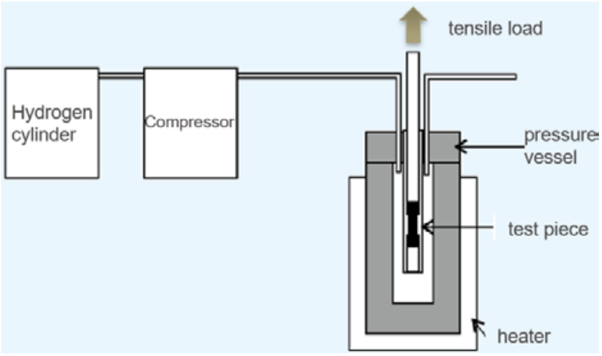


Figure 7 Outline of SSRT Test Apparatus

Test conditions include pressure, temperature, and hydrogen concentration. SSRT tests were conducted under the same conditions as the actual engine operating environment and under the air environment, and the effect of hydrogen embrittlement was confirmed. An example of the test results is shown in Figure 8.

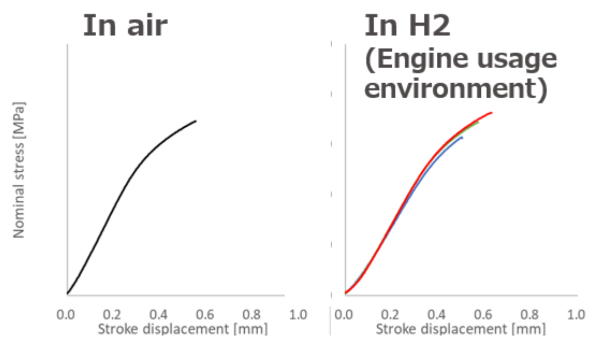


Figure 8 SSRT test results

As a result of the test, it was confirmed that there was no difference in nominal stress and stroke displacement between the air environment and the engine environment. As a result, it was judged that this material could be used in the same way as a natural gas engine because there was no deterioration in strength due to the effect of hydrogen in the engine operating environment.

## 5 MULTI CYLINDER ENGINE DESIGN

The design of the multi-cylinder engine was implemented reflecting the content of "Development of hydrogen gas engine" in Section 4. Different from the single cylinder test engine, there is a point to be noticed in the design of the multi-cylinder engine. The following design points are described in detail in this section.

- ✓ High intake and exhaust efficiency system
- ✓ Reduction of EGR dispersion between cylinders
- ✓ Modularization of turbocharger and EGR system

### 5.1 Maintaining high intake and exhaust efficiency

Since the developed engine is a dual-fuel engine, there are two operation modes: D-mode operation and H-mode operation. Figures 9 and 10 show the intake and exhaust system and the EGR system for each operating mode.

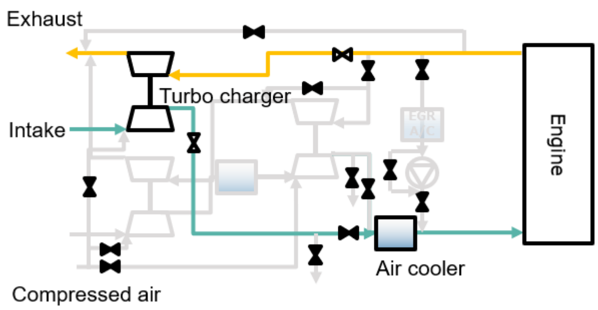


Figure 9 Intake and exhaust system for D-mode

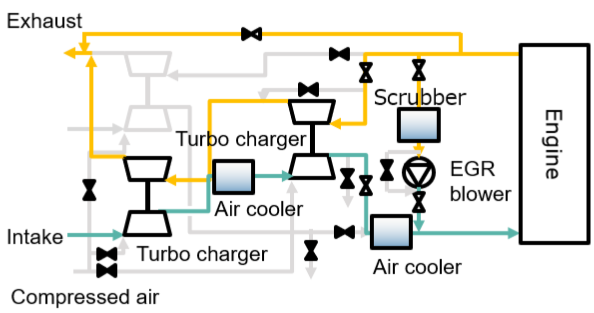


Figure 10 Intake and exhaust system for H-mode

In D-mode operation, EGR is not applied, but in H-mode operation, EGR is applied as an abnormal combustion control technology. In the case where EGR is applied, the amount of exhaust air flowing through the turbocharger turbine is significantly different from the case where EGR is not applied, so that a single turbocharger cannot maintain high intake and exhaust efficiency. Therefore, the turbocharger for D-mode operation and H-mode operation were selected separately in the developed engine. In the H-mode operation, the turbocharger is small because the exhaust air volume is small, and the turbocharger efficiency is low. Therefore, the efficiency of the turbocharger is improved by using two-stage turbocharging. It is important to increase the turbocharger efficiency because abnormal combustion occurs when the turbocharger efficiency is low in H-mode operation.

### 5.2 Reduction of EGR dispersion between cylinders

The dispersion between cylinders of EGR is generated in the multi-cylinder engine. It is important to reduce the variation between the EGR cylinders because the combustion varies greatly when the variation is large. In order to minimize the dispersion of EGR, a CFD analysis was performed to optimize the nozzle to merge EGR into fresh air. The CFD analysis results are shown in Figures 11 and 12.

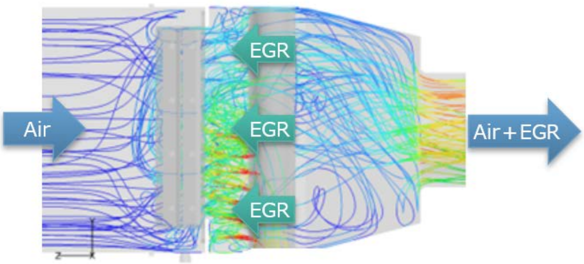


Figure 11 EGR mixing analysis results 1

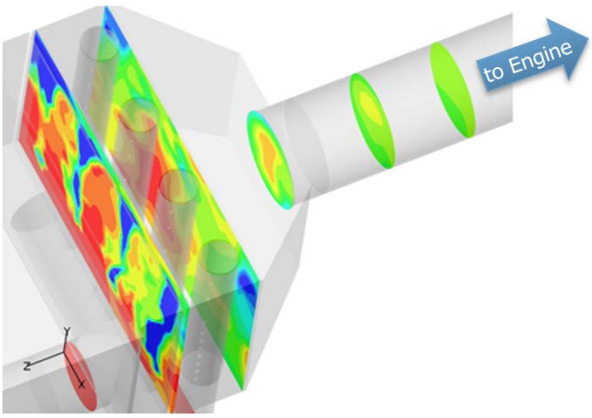


Figure 12 EGR mixing analysis results 2

EGR could be mixed uniformly by injecting from many nozzles with the injection nozzles facing the direction opposite to the flow of fresh air.

### 5.3 Modularization of turbocharger and EGR system

The developed engine has a large number of engine accessories due to multiple turbochargers and the EGR system. Therefore, the design was carried out to make these equipments into one module. The modular of turbocharger and EGR system are shown in Figure 13.

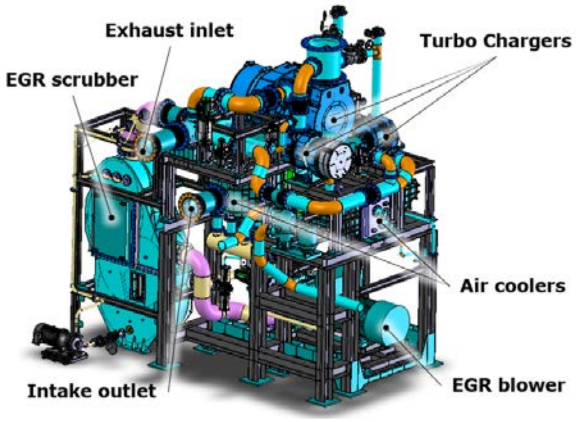


Figure 13 The modular of turbocharger and EGR system

Three turbochargers were arranged in the upper stage, and are air-coolers was arranged in the middle stage. An EGR blower was installed in the lower stage to secure the necessary maintenance space. The EGR scrubber is placed closest to the engine to minimize pressure loss. This module has an excessive specification because it was manufactured experimentally for the test. We plan to optimize the performance and make it compact in the future shop test.

## 6 SHOP DEMONSTRATION TEST

The trial run facility is now being prepared for the shop demonstration test of the multi-cylinder test engine designed in Section 5. Since the developed engine consumes a large amount of hydrogen, a liquefied hydrogen storage facility shown in Figure 14 is newly installed and hydrogen is supplied from there. Photographs of the onshore demonstration facility are shown in Figures 15 and 16.

Figure 14 Hydrogen supply equipment

Figure 15 Engine test yard

Figure 16 Multi-cylinder engine (around cylinder head)

The test will start in D mode operation from January 2025, and then shift to H mode operation. Shop tests will be conducted for about a year, and various performance and function evaluations will be conducted.

## 7 CONCLUSION

This project was commissioned by the New Energy and Industrial Technology Development Organization "Green Innovation Fund Project/Development of Next-Generation Ships/Development of Hydrogen-Fueled Ships." We are now in the phase of shop demonstration tests. After that, it is planned to mount the newly developed engine on a ship for demonstration tests. Development is underway with the aim of commercialization around 2030.