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A large-scale development of GHG reduction technology by ammonia- and hydrogen-fueled engines

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

Greenhouse gas (GHG) reduction is a challenge that the marine industry has never faced before. In research on drastic reduction of GHG, ammonia and hydrogen have attracted global attention as alternative fuels. Because these are carbon-free fuels, the adoption of these fuels in propulsion internal combustion engines is expected to be one of the effective solutions to realize carbon-free shipping.

Therefore, J-ENG (Japan Engine Corporation) is developing ammonia- and hydrogen-fueled low-speed two-stroke engines on a large scale as a key member of the "Green Innovation Fund Projects" supported by NEDO, New Energy and Industrial Technology Development Organization, Japan. This paper describes the status of these developments in detail.

Ammonia has the properties of high latent heat that cools the surrounding atmosphere when evaporated, high ignition temperature (requires high ignition energy), slow burning rate, and poor flame retention. In addition, nitrous oxide (N2O) can be emitted from the combustion of ammonia, which has a greenhouse effect about 300 times that of CO2. In order to address these properties, various tests on originally developed fuel injection and combustion systems have been carried out using analytical simulations and single-cylinder test machines. This paper describes the results of those studies and the development status of full-scale engines using those knowledges.

Hydrogen has the properties of high auto-ignition temperature but low minimum ignition energy and fast burning rate. In addition to its combustion properties, hydrogen has the embrittlement properties that make some material brittle. In order to address these properties, basic research has been conducted in collaboration with universities and consortium companies.

J-ENG is developing the world’s first diesel-cycle type hydrogen-fueled low-speed two-stroke engine, which realizes high power and high efficiency without worrying about the back-firing, pre-ignition and knocking associated with Otto-cycle type hydrogen combustion. For the development of a full-scale engine, analytical simulations and a hydrogen injection unit test device have been used to develop an injection system and conduct durability verification. This paper describes the results of these research and the development status of the full-scale engine.

1 INTRODUCTION

In July 2023, the IMO adopted the "2023 Strategy on Reduction of GHG Emissions from Ships" which shows the indicative checkpoints, 20% to 30% reduction by 2030, 70% to 80% reduction by 2040 compared to 2008 to achieve net-zero GHG emissions by or around 2050.

To achieve that, considering the service life of ships, the early adoption of zero GHG emission ship is required.

Alternative fuels such as LNG, LPG, and methanol are seen as promising bridge solutions, but the GHG reduction rate is only a few percent to around 20%, therefore carbon-free fuels are required. Under these circumstances, J-ENG is developing the carbon-free fueled engines, Ammonia fueled engine and Hydrogen fueled engine as shown in Figure 1.

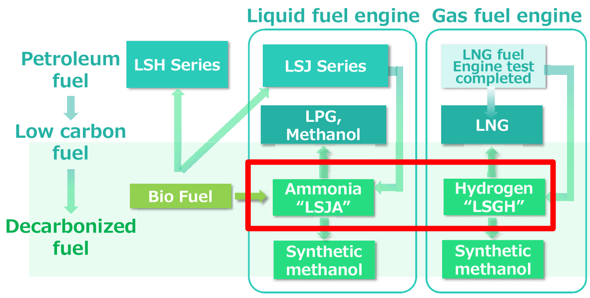

Figure 1. Carbon neutral strategy for UE Engine

2 AMMONIA-FUELED ENGINE

2.1 Framework of the project

J-ENG is developing an ammonia fueled engine named UEC-LSJA, as a member of the exclusively organized domestic consortium. The consortium consists of Nippon Yusen Kabushiki Kaisha (NYK Line), J-ENG, IHI Power Systems Co., Ltd., and Nihon Shipyard Co., Ltd.

And this project is financially supported by Japanese Government, Namely, Green Innovation Fund of New Energy and Industrial Technology Development Organization (NEDO).

Figure 2 shows the development schedule for ammonia-fueled engine.

The engine under development is 50 cm bore size named UEC50LSJA.

In this project, J-ENG is planning to complete the engine in 2025. And this engine will be installed in the Ammonia Fueled Medium Gas Carrier (AFMGC) which is designed by Nihon Shipyard and is built by Japan Marine United Corporation. And it will be owned by NYK Line.

The vessel is planned to go into service in FY2026.

Along this project, J-ENG completed test operations of single cylinder test engine and currently manufacturing of the first ammonia-fueled full-scale engine provided feedback from these results is progressing and its trial operation scheduled to begin in April 2025 and completed in September 2025.

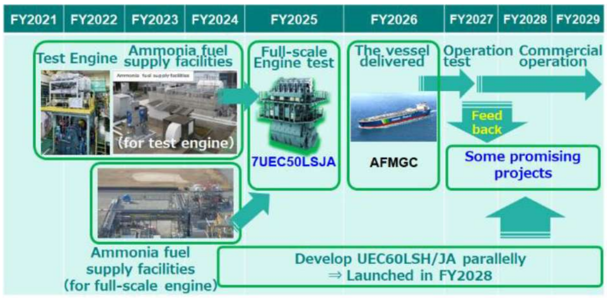

Figure 2. Development schedule for ammonia-fueled engine

2.2 Technical issues and countermeasures of ammonia fuel

Figure 3 shows the technical issues and the countermeasures of ammonia fuel.

Ammonia has a slow burning rate (1/5 that of methane) and a high spontaneous ignition temperature of 651 °C. During incomplete combustion, there are concerns that nitrous oxide (N_2O), which has a global warming potential approximately 265 times that of CO_2, are generated. Therefore, a certain amount of pilot fuel will be needed and it is important that ammonia is effectively burned with smaller amount of pilot fuel oil.

Ammonia is highly irritating to mucous membranes and can cause severe damage to the respiratory tract and lungs in a short period of time. It is necessary to apply safety measures such as double piping, purge equipment, and separation and recovery equipment. Purge equipment is the device which sends an inert gas into the space to remove the ammonia gas that has been accumulated in the space.

Since no international regulations for ammonia-fueled vessel have yet been established at development stage, the consortium of AFMGC aim to obtain approval of an alternative design, the design is equivalent to the safety requirements of the existing international regulations.

The consortium conducted a HAZID risk assessment for the safety of using ammonia as marine fuel and received an AiP (Approval in Principle) from ClassNK.

IMO guidelines for vessels using ammonia as fuel was approved at the 109th session of the IMO Maritime Safety Committee (MSC109) in Dec. 2024.

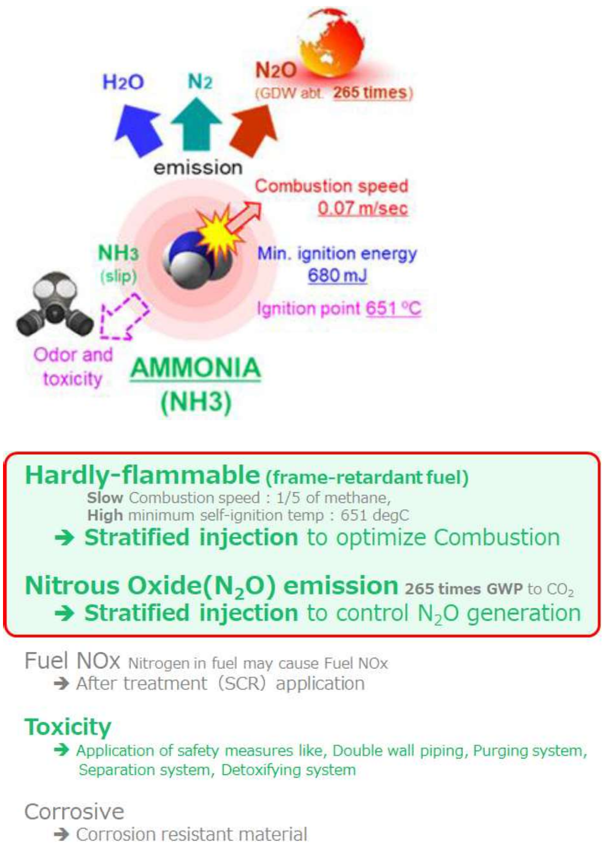

Figure 3. Technical issues of ammonia

2.3 Combustion method of ammonia fuel

In J-ENG's ammonia-fueled engines, the diesel cycle is adopted because it is possible to secure time for the liquid ammonia to be injected and evaporated in the cylinder due to its lower rotating speed. The diesel cycle is that in which high-pressure fuel is injected into compressed air that has been compressed to a high temperature, and the evaporated fuel is ignited by itself or by some pilot fuel, which is also called diffusion combustion. The advantage of the diffusion combustion method is that it is possible to aim for ammonia calorific ratio in spite of its flame-retardant characteristic and to reduce the slip of unburned ammonia.

The ammonia-fueled engine applied stratified injection system to promote the ignition of ammonia fuel and combustion after the end of ammonia fuel injection.

Figure 4 shows an example of a CFD (Computational Fluid Dynamics) analysis of fuel spray. First sprayed red colored pilot fuel envelops yellow colored Ammonia spray, during spray formation process. This process ensures good Ammonia ignition and maintain a stable flame. And last sprayed blue colored post fuel pushes out Ammonia spray toward the outside Ammonia flame, then activates Ammonia combustion to the last. With this stratified fuel spraying and combustion process, it is certain that good ammonia combustion and less N_2O emission with moderate amount of pilot / post fuel can be effectively realized.

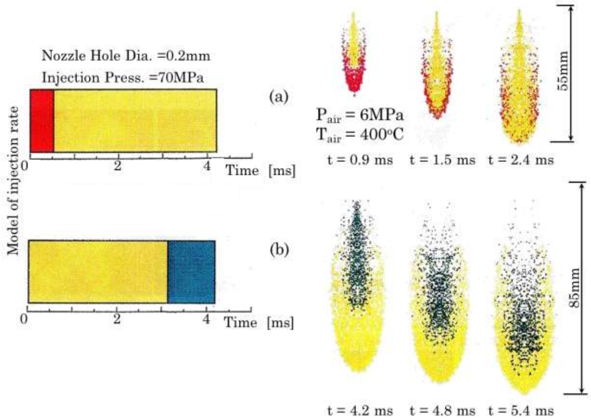

Figure 4. Example of CFD analysis of fuel spray[2]

2.4 Test results of single cylinder test engine

Figure 5 shows the ammonia-fueled test engine and the ammonia fuel supply facilities.

J-ENG started the world's first ammonia co-firing operation of a large low-speed 2-stroke engine in May 2023 and completed the test in September 2024.

Through these tests, J-ENG has achieved stable operation of the engine at a high ammonia co-firing rate and has confirmed that the generation of nitrous oxide (N2O), which has high global warming potential, can be suppressed to a very low level through combustion controls. The following results have been achieved.

- Stable operation with a low pilot fuel oil rate
- Very low level of nitrous oxide (N_2O)
- Approx. 90% GHG reduction
- Lower NOx emissions compared with heavy fuel oil
- Ammonia slip after SCR is acceptable.

- Normal condition of piston rings and cylinder liner
- Suitable O-ring and metal material for corrosion

Figure 6 and 7 show the cylinder pressure curve of ammonia mode and fuel oil mode.

J-ENG will finally verify the performance on the full-scale ammonia-fueled engine test.

Furthermore, J-ENG has also completed verification of peripheral equipment such as the ammonia fuel supply, including the functionality and safety, maintainability of each piece of equipment, and the fuel switching sequence between heavy oil and ammonia, and have achieved many results regarding the safe handling of toxic ammonia.

Figure 5. Ammonia-fueled test engine, Ammonia fuel supply facilities

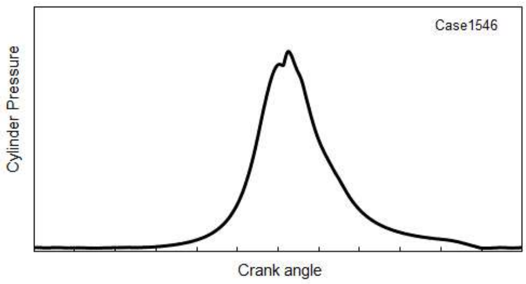

Figure 6. Cylinder pressure curve of ammonia mode

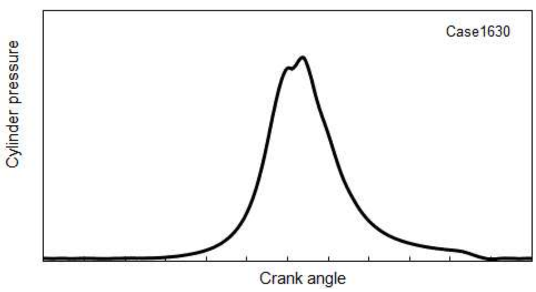

Figure 7. Cylinder pressure curve of fuel oil mode

2.5 Full-scale ammonia-fueled engine

The first ammonia-fueled full-scale engine, UEC50LSJA will be completed in September 2025 through around 6 months verification operation at our factory. This engine is designed as a dual-fuel engine equipped with a supply system for both heavy fuel oil and ammonia fuel, and ammonia fuel is burned by heavy fuel oil as pilot fuel in the ammonia fuel operation mode.

It is believed that the need for ammonia-fueled ship will continue to grow in the future and the construction of VLAC (Very Large Ammonia Carrier) is also expected to increase. To meet the market need of the various ship type, J-ENG are also developing a large size ammonia-fueled engine, UEC60LSJA having 60cm bore. This engine type is optimal for the various ship types, VLAC, Car carrier, VLGC(Very Large Gas Carrier), Capesize bulk carrier, Coal carrier and so on.

Figure 8 shows the image of UEC50LSJA.

J-ENG is the only licensor in the world with an integrated business scheme from development and manufacturing to after-sales service, which is our big advantage for ammonia-fueled engine as well.

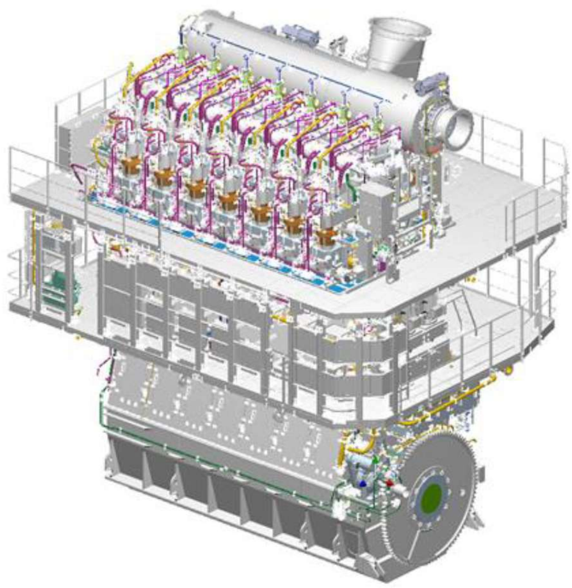

Figure 8. UEC50LSJA

3 HYDROGEN-FUELED ENGINE

3.1 Framework of the project

J-ENG is developing hydrogen fueled engines which will be the world’s first main engine for large ocean-going or coastal vessels, by forming a consortium with Kawasaki Heavy Industries, Ltd. and Yanmar Power Technology Co., Ltd. and established a joint development company HyENG Corporation with them in 2021.

The engine development is also financially supported by Japanese Government, Namely, Green Innovation Fund of New Energy and Industrial Technology Development Organization (NEDO).

Figure 9 shows the development schedule for hydrogen-fueled engine.

The first hydrogen-fueled engine, UEC35LSGH with a bore of 35cm, is expected to complete in FY2026. And this engine will be installed in Multi-Purpose vessel which is planning to start the demonstration operation in FY2027.

The vessel will be operated by Mitsui O.S.K. Lines, Ltd. (MOL) and MOL Drybulk, Ltd., aiming to commercialize net zero hydrogen-powered vessels and promote their wide adoption in the ocean shipping industry.

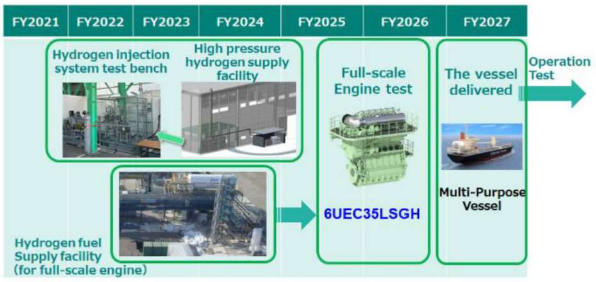

Figure 9. Development schedule for hydrogen-fueled engine

3.2 Technical issues and countermeasures of hydrogen fuel

Figure 10 shows the technical issues and the countermeasures of hydrogen fuel.

Hydrogen has a low self-ignition temperature and a very high combustion speed, so even a very small amount of ignition source can ignite it, preventing abnormal combustion and stably controlling fuel is a key factor in the technological development.

Engine parts have the risk of not being able to secure the expected reliability due to hydrogen embrittlement, so it is necessary to use appropriate materials that are not affected by hydrogen embrittlement.

Since hydrogen has the smallest molecular weight among all substances, it has the characteristic of leaking easily. Therefore, it is necessary to construct appropriate sealing technology and take measures to prevent leakage.

Since no international regulations for hydrogen-fueled vessel have yet been established, the consortium aims to obtain approval of an alternative design, the design is equivalent to the safety requirements of the existing international regulations.

The consortium conducted a Pre-HAZID risk assessment for identification of the risks and issues to be considered in further design for the parcel layout concept of liquefied hydrogen fuel tank and fuel supply system, and confirmed that the design of the vessel can proceed further based on the current parcel layout.

The consortium received AiP of parcel layout concept from ClassNK. This is the world's first AiP certification for a ship equipped with a low speed two-stroke hydrogen-fueled engine as the main propulsion engine.

After progressing to design based on the parcel layout, HAZID risk assessment for whole system of the vessel including hydrogen-fueled engine of the vessel has been done and the measures for the identified risks and issues have been determined.

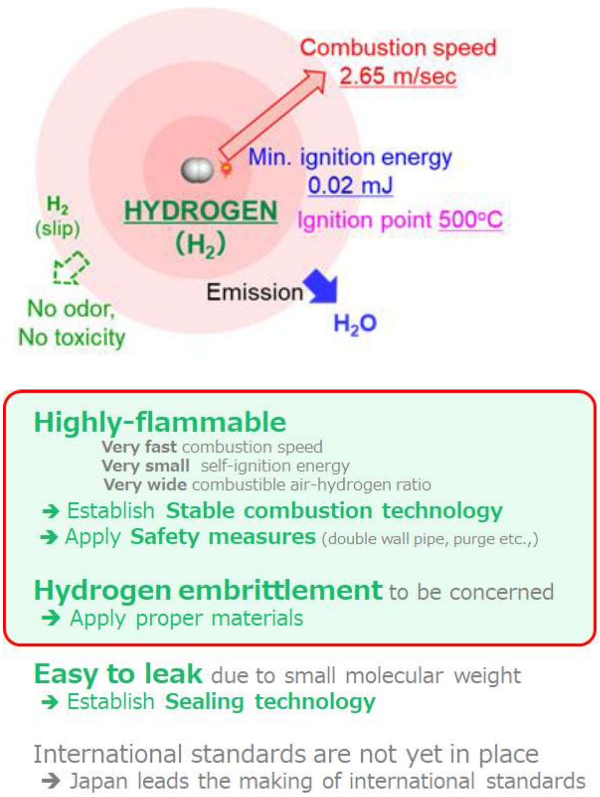

Figure 10. Technical issues of hydrogen

3.3 Combustion method of hydrogen fuel

Figure 11 shows representative gas injection methods possible for 2 stroke engines, which are "High pressure gas injection" and "Premixing".

If hydrogen is premixed and combusted in a low-speed two-stroke engine, unburned hydrogen is exposed to high temperature and high pressure in the combustion chamber in one cycle since the low-speed engines have a rotation speed of approximately 1/10 of that of the medium- and high-speed 4-stroke engines. As the duration exposed to such environment is approximately 10 times longer, the risk of abnormal combustion such as ignition of hydrogen at an unexpectedly early timing is extremely high.

One of the solutions to this problem is to limit the engine output in order to alleviate the high-temperature and high-pressure conditions in the combustion chamber. On the other hand, the engine size must be increased to obtain the same power output. That solution is not preferable.

To avoid the disadvantage of premixing method, high-pressure (about 30MPa) injection method is applied to J-ENG's hydrogen fueled engines. By this method, stable combustion can be achieved since hydrogen is directly injected into the combustion chamber at the timing, when the combustion chamber reaches high-temperature and high-pressure.

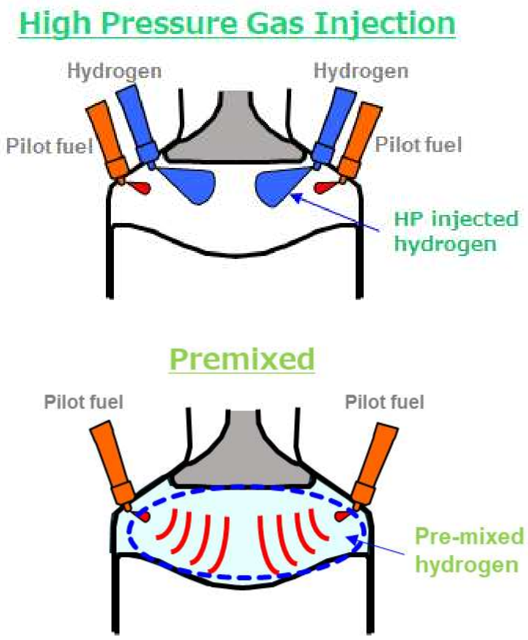

Figure 11. Hydrogen gas injection method

3.4 Combustion simulation using injection and combustion test

To evaluate the high press hydrogen combustion properties, the combustion simulation was established based on the results of combustion visualization tests using a test device, RCEM (Rapid Compression Expansion Machine) with Kyushu University.

Figure 12 shows the schematic of RCEM. High-pressure hydrogen gas and pilot gas oil are injected into the high-temperature and high-pressure air generated by RCEM, and the combusted hydrogen gas is visualized using shadow-graph method.

Figure 13 shows the schematic of visualization area of RCEM.

Table 1 shows the injection parameters of pilot gas oil and hydrogen gas.

Figure 14 shows the comparison of visualization images and simulation results of hydrogen combustion. The simulation can reproduce the combustion test. And the relation of hydrogen fuel consumption and NOx emissions are being evaluated with the simulation.

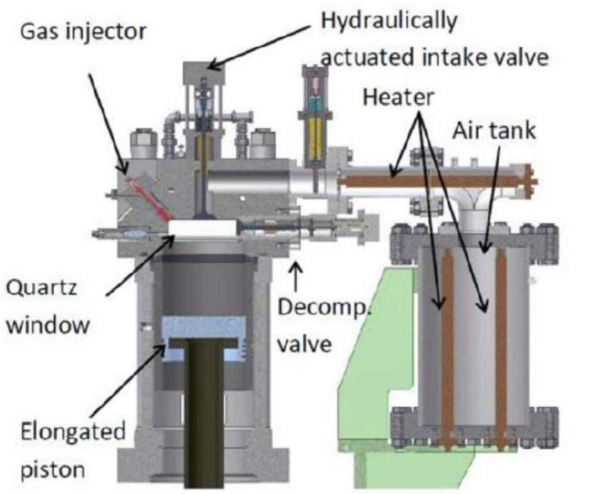

Figure 12. Schematic of combustion visualization test device (RCEM)

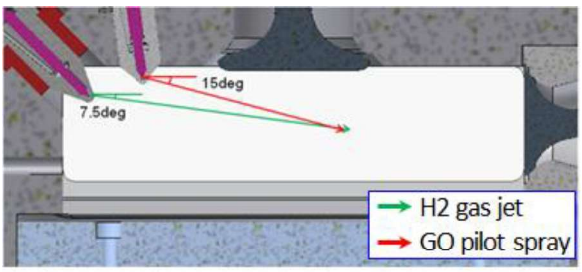

Figure 13. Schematic of visualization area of RCEM

Table 1. Injection parameters of pilot gas oil and hydrogen gas

	GO pilot	H2 main
Nozzle holes	∅0.16 mm × 1	∅1.6 mm × 1
Injection pressure	70 MPa	30 MPa
Injection timing	0 deg. ATDC (TDC)	1.5 deg. ATDC
Injection duration	12 deg. CA	20 deg. CA
Air excess ratio	λ_{plt} ~230	λ_{H2} ~3.8
Comp. end conds.	500 °C, 6 MPa	

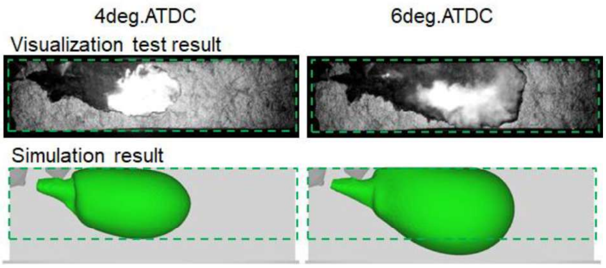

Figure 14. Comparison of visualization images (upper image) and simulation results (lower image) of hydrogen combustion

3.5 Hydrogen embrittlement properties under high-pressure hydrogen gas environment

The consortium conducted the hydrogen embrittlement material test with Kyushu University.

Figure 15. shows the result of SSRT (Slow Strain Rate Testing) of high strength alloy steel which is planned to be used for the needle and nozzle of gas injection valve. The tensile strength in 30MPa H2 is about half of that in air by hydrogen embrittlement. However, the tensile strength in 30MPa H2 is quite lower than the stress generated at the used part.

Figure 16. shows the result of resonance fatigue test of high strength alloy steel. The fatigue strength in 30MPa H2 is equivalent with that in air. high strength alloy steel is expected to be usable for the needle and nozzle of gas injection valve.

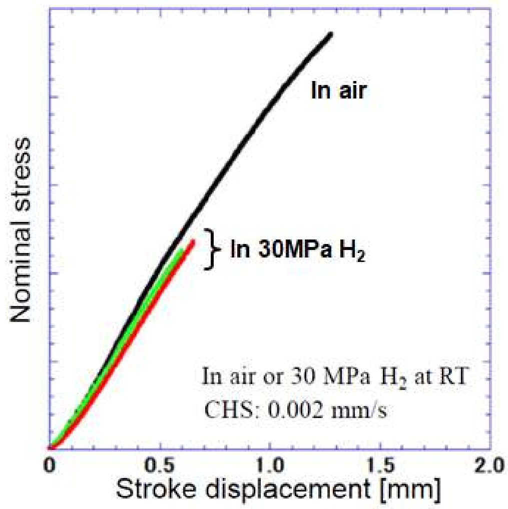

Figure 15. SSRT test result (Stress-displacement curve)

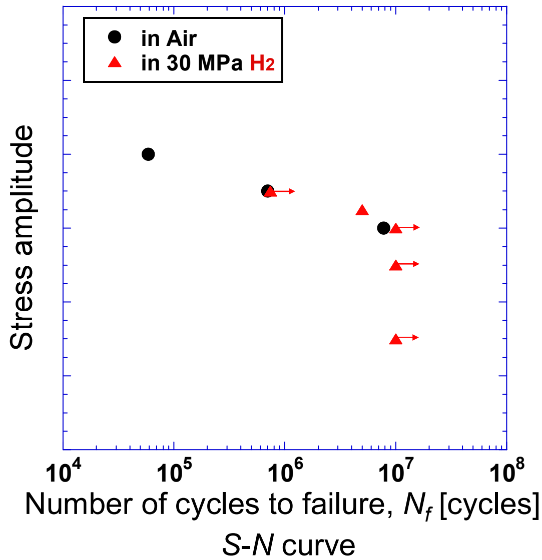

Figure 16. Resonance fatigue test result

3.6 Test results of hydrogen injection system test bench

Long-term durability test was conducted on the high-pressure hydrogen injection system test bench without combustion.

Figure 17 shows the schematic and photograph of hydrogen injection test bench.

Figure 18 and 19 show the inspection results after long-term durability test of Gas Injection Valve (GIV) and Gas Gate Valve (GGV).

It was confirmed that the materials of GIV and GGV are usable in 30MPa H2 based on the long-term durability test.

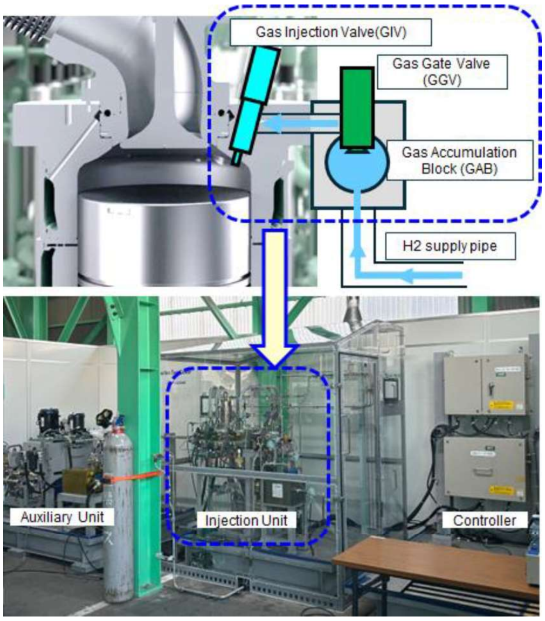

Figure 17. Hydrogen injection system test bench (without combustion)

Figure 18. Condition of Gas Injection Valve

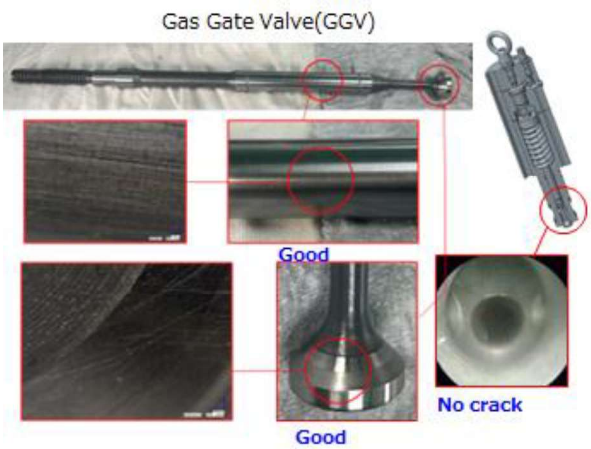

Figure 19. Condition of Gas Gate Valve

3.7 Full-scale hydrogen-fueled engine

The first hydrogen-fueled full-scale engine, UEC35LSGH will be completed in FY2026 through around 1 year verification operation at our factory. This engine is designed as a dual-fuel engine equipped with a supply system for both heavy fuel oil and hydrogen fuel, and hydrogen fuel is burned by heavy fuel oil as pilot fuel in the hydrogen fuel operation mode.

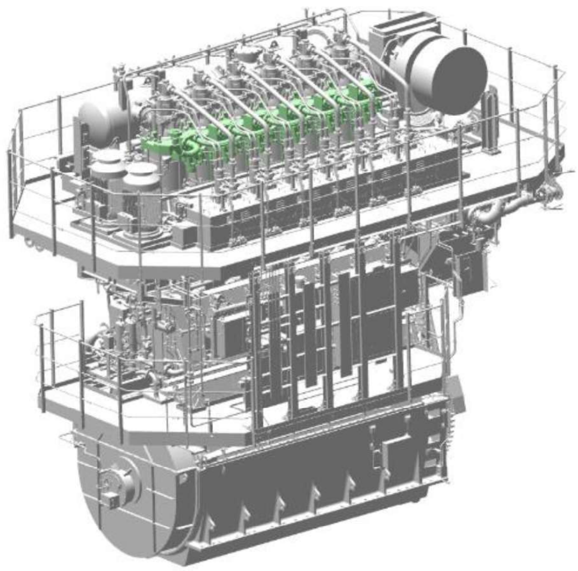

Figure 20. UEC35LSGH

4 CONCLUSIONS

Aiming for carbon neutrality in 2050, the need for carbon-free fueled engines is expected to increase in the future. J-ENG are developing ammonia-fueled engine and hydrogen-fueled engine.

Ammonia-fueled engine, UEC50LSJA will be completed in September 2025. And this engine will be installed in AFMGC which is planning to start the demonstration operation in FY2026.

Hydrogen-fueled engine, UEC35LSGH will be completed in FY2026. And this engine will be installed in Multi-Purpose vessel which is planning to start the demonstration operation in FY2027.

J-ENG will contribute to reducing GHG in the maritime industry and achieving carbon neutrality by 2050 through the early market launch of the carbon-free fueled engines.

5 ACKNOWLEDGMENTS

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And the development of a hydrogen fueled engine in this paper is commissioned by the New Energy and Industrial Technology Development Organization (NEDO) (Project No. JPNP 21501814-0).

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