Trends in Development of Marine Dual Fuel Engines to Reduce GHG Emissions

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1. INTRODUCTION

This paper is a follow-up to the author's previous paper "Studies on In-Engine Combustion of Low and Zero Carbon Fuels" in ClassNK Technical Report No. 7 published in 2023. Toward achievement of the IMO's target of "Net zero GHG emissions from international shipping in 2050," ClassNK Alternative Fuels Insight ("NK Insight") was published in 2024. This paper may be useful for understanding the steps in applying alternative fuels to international shipping described in the NK Insight.

As stated in NK Insight, there is an overwhelming shortage of alternative fuel production at present. However, in order to achieve the 2050 target, the development of marine engines that can use alternative fuels must be pursued now, with a view to increasing the scale of alternative fuel production in the future. Continuing from the previous paper, this paper describes the development of marine engines that use zero-emission (zero-carbon) and carbon-neutral fuels, including the progress made in Japan under the Green Innovation Fund Project for the Development of Next-Generation Ships (hereinafter, GI Fund) by the New Energy and Industrial Technology Development Organization (NEDO), and also touches on trends in development on the European side.

The definition of Dual Fuel engines in this paper is engines that can use both an alternative fuel and heavy fuel oil, and may operate on heavy fuel oil until the alternative fuel supply system is in place. For this purpose, sufficient capacity of heavy fuel oil tanks should be maintained on board. In addition, since the self-ignition properties of all possible alternative fuels are inferior to those of heavy fuel oil, a small amount of heavy fuel oil must be injected as pilot fuel for ignition in the cylinder. If the supply of alternative fuels is insufficient, it is possible to actively increase the amount of heavy fuel oil injected to create so-called "mixed combustion with an alternative fuel and heavy fuel oil."

2. ZERO-EMISSION FUELS AND CARBON-NEUTRAL FUELS

<u>Zero-emission fuels</u> include green hydrogen, which is produced by electrolyzing water with renewable electricity, and blue hydrogen, which can be made from fossil fuels, provided the CO_2 emitted during production is captured and stored. A project to produce hydrogen from Australian brown coal, which has a high water content, liquefy the hydrogen, and transport it to Japan is an example of the use of blue hydrogen. Ammonia (NH_3), which is synthesized from hydrogen and nitrogen, is also a zero-emission fuel.

<u>Carbon-neutral fuels</u> include the following. Biofuels emit CO_2 during combustion, but are zero-counted because they have absorbed CO_2 from the atmosphere before combustion. Synthetic methane and synthetic methanol were described in the previous paper, but it is expected that regulations will be enacted to allow zero-counting of CO_2 from ships using fuels synthesized from green or blue hydrogen and CO_2 recycled from land-based industries (in that case, the land side would have emitted the CO_2). The IMO begins discussions of this issue.

There is also the idea that, in the absence of actual supplies of such synthetic fuels, grey fuels (fossil natural gas or methanol made from fossil fuels) may be used for the time being, and then switched to green or blue ones as soon as they become available. This is explained below.

<u>Biofuels</u>: According to NK Insight, methane, LPG and methanol can be produced from bio-based sources in addition to the synthetic methods mentioned above. However, only biodiesel oil, which is also being tested and used at present, is discussed here. There are few combustion problems in engines when vegetable oil is processed to FAME (Fatty Acid Methyl Ester), which can be used by conventional heavy oil-fueled diesel engines as a drop-in, i.e., without changing the engine side settings. It can also be mixed with heavy fuel oil for bunkering. However, the amount of raw material is an issue. There is much opposition

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worldwide to the direct conversion of cooking oil into fuel, and at present the aviation industry is competing for waste cooking oil as a raw material.

For reference, the Maritime Bureau of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) and ClassNK have revised the following guides on the handling of biofuels, respectively.

・Maritime Bureau, MLIT: Guidelines for handling biofuels, revised March 2024 [1)]

・ClassNK: Technical Guide for Using Biofuels (Edition 1.1), revised in April 2024 [2)]

Synthetic methane: Synthetic methane is a drop-in for existing LNG-fueled vessels, as methane is the main component of the natural gas currently in use. There is a view that fossil LNG-fueled vessels should be built at present and converted to synthetic methane as soon as it emerges.

Synthetic methanol: Methanol has the advantage of being a liquid at ambient temperature and pressure. Methanol engines require pilot fuel due to the higher self-ignition temperature of methanol, but once ignited, methanol shows better combustion characteristics than diesel oil. The low-speed, two-stroke methanol engine developed by MAN Energy Solutions (MAN) has already been in operation since 2016 as the main engine of methanol carriers.

The high cost of both synthetic methane and synthetic methanol is an issue due to the aforementioned production process, and according to NK Insight's “Production pathways and costs of alternative fuels (costs are projected as of 2030),” the cost of both is estimated to be 4.2 times higher than that of conventional heavy fuel oil.

Ammonia: Both low-speed, two-stroke and medium-speed, four-stroke engines are currently under development, as will be discussed later. NK Insight estimates the cost of green ammonia to be 3.1 times that of conventional heavy fuel oil and the cost of blue ammonia is 1.9 times higher. As mentioned above, a supply chain of green or blue ammonia is urgently needed, even if grey ammonia is allowed to be used at first.

The Maritime Bureau of MLIT has been holding meetings of an Ammonia Bunkering Guideline Study Committee since last year [3)] to implement safe and smooth bunkering of ammonia-fueled ships, and is giving sufficient consideration to measures against leakage, especially in view of the toxicity of ammonia.

Hydrogen: Hydrogen engines are also under development as both low-speed, two-stroke and medium-speed, four-stroke types, as discussed below. In comparison with conventional heavy fuel oil, NK Insight estimates the cost to be 3.8 times higher for liquefied green hydrogen and 3.1 times higher for liquefied blue hydrogen. As hydrogen is also relatively expensive compared to ammonia, reducing the cost of liquefaction is a challenge at present.

In addition, due to issues such as the capacity of on-board liquefied hydrogen tanks, the development of hydrogen engines under the GI Fund is initially planned for use on liquefied hydrogen carriers and for short sea shipping routes such as those between Japan and South East Asia.

Which of these alternative fuels will be the main one? Many research institutes around the world predict that all will remain in 2050. Against this background, this paper describes the development of methanol, ammonia and hydrogen combustion engines.

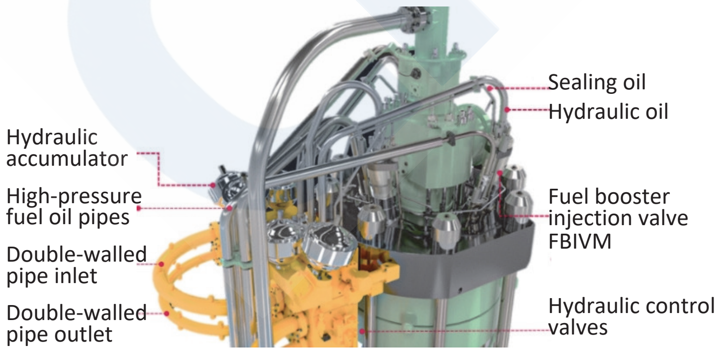


Fig. 1 MAN low-speed, two-stroke methanol engine G95ME-C10.5-LGIM (cylinder diameter: 950 mm), showing the cylinder cover section (courtesy of MAN ES)

Fig. 2 Single-cylinder test engine SCE920 (cylinder diameter: 920 mm) for WinGD's low-speed, two-stroke methanol engine development (courtesy of WinGD)

3. TRENDS IN THE DEVELOPMENT OF METHANOL (CH_3OH) DF ENGINES

3.1 Low-speed, Two-stroke Methanol Engines

To begin with, the diesel-type methanol engine will be described. Both MAN and WinGD are developing low-speed, two-stroke main engines of this type. The properties of methanol and diesel spray combustion were described in the previous paper. Methanol has a boiling point of 65 °C at ambient pressure and can be fed as a liquid to the engine at line pressure (1.3 MPa according to Mitsui E&S [4]), allowing normal diesel injection into the cylinder. However, as the calorific value per volume is approximately 40 % that of heavy fuel oil, a system that injects 2.5 times the volume is required to achieve the same output.

Methanol has a low flash point of 9 °C, but a high ignition point (self-ignition temperature) of 440 °C, requiring pilot injection of diesel oil for ignition in the cylinder. However, as shown in the previous paper, once ignited, it shows better combustion characteristics than gas oil. As mentioned above, low-speed, two-stroke engines developed by MAN are already in service and are technically at the stage of completion, and many orders have been placed recently, particularly for large containerships.

Fig. 1 shows the cylinder cover of an engine with a cylinder diameter of 950 mm developed as the main engine for large container vessels. The 'DF' features three pairs of methanol and heavy fuel oil injection nozzles. The orange part indicates the double-walled pipe section, which is provided as a countermeasure against leakage of low flash point, high toxicity methanol [5].

WinGD has also been conducting combustion rig tests and development work using a four-cylinder test engine (cylinder diameter: 500 mm) for alcohol (ethanol and methanol) fueled main engines since 2015. It is conducting verification with a single-cylinder test engine (Fig. 2, cylinder diameter: 920 mm), and plans operation tests of 10X92DF-M engines with ten cylinders of the same diameter for large containerships in the first quarter of 2025 [6].

3.2 Medium-speed, Four-stroke Methanol Engines

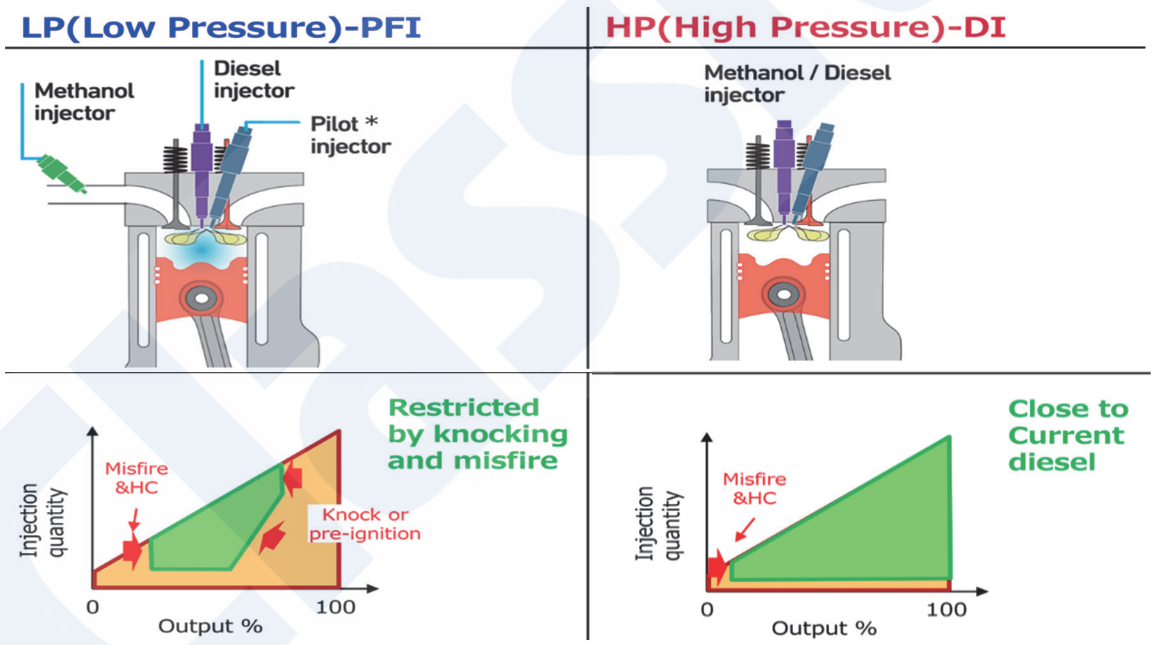


Fig. 3 Two combustion patterns for medium-speed, four-stroke methanol engines [7]

Medium-speed, four-stroke methanol engines are being developed for onboard generators or as main engines of small and medium-sized vessels. The combustion patterns of the diesel type and the Otto-cycle type are introduced here using Fig. 3.

In diesel-type combustion (right half of Fig. 3: HP (High-Pressure)-DI (Direct Injection)), high-pressure liquid methanol is injected into the high-pressure air compressed by the piston to create a spray combustion process. In addition to the injection system for diesel oil, a methanol injection system with an injection volume of 2.5 times that of diesel fuel is required, as already mentioned. The advantage of the diesel-type over the Otto-cycle type is that abnormal combustion such as knocking does not occur, so it is possible to aim for high output (high Pme: mean effective pressure) and high efficiency.

In Otto-cycle combustion (left-half of Fig. 3: LP(Low-Pressure)-PFI(Port Fuel Injection)), methanol is injected into the intake port, and the vaporized methanol and air mixture is compressed by the piston and then ignited by pilot injection to start flame propagation. The low-pressure injection system for the intake port is simpler and easier to retrofit than the diesel-type high-pressure injection system. However, as knocking, etc. may occur, the methanol percentage and the power range with methanol tend to be restricted, as shown in the diagram at the bottom left in Fig. 3 (the green and brown areas in the diagram are the methanol and diesel oil use ranges, respectively).

YANMAR POWER TECHNOLOGY CO., LTD. (YANMAR) and DAIHATSU DIESEL MFG. CO., LTD. (DAIHATSU DIESEL) in Japan have compared both combustion patterns using test engines and presented their results [7), 8)]. Both companies have also announced plans to launch engines compatible with methanol fuel in 2026.

HANSHIN DIESEL WORKS, LTD. has already developed a low-speed, four-stroke engine, LA28M, with a cylinder diameter of 280 mm. This engine is the diesel type and targets a methanol mono-fuel engine instead of DF. However, even when methanol is not used, redundancy is ensured by increasing the amount of marine diesel oil which is originally used for pilot use, making it possible to sail at the speed required by the classification [9)].

Furthermore, AKASAKA Diesels Limited is also developing a low-speed, four-stroke diesel-type methanol DF engine [10)], for which an electronically controlled common-rail methanol injection system will be applied.

On the European side, MAN has developed L21/31DF-M (cylinder diameter: 210 mm) and L27/38DF-M (cylinder diameter: 270 mm) engines with generator-set specifications by applying the Otto cycle type. MAN is also announcing that it will start offering retrofit packages for conversion of larger four-stroke conventional models to methanol DF [11)].

The Wartsila 32 (cylinder diameter: 320 mm) methanol engine applying the diesel type has already been developed and released by Wartsila, a pioneer in this field, and a method for converting conventionally-fueled vessels to methanol fuel has also been announced [12)].

In the case of diesel-type four-stroke engines, the fuel injection nozzle must be installed in the center of the cylinder head, unlike low-speed, two-stroke engines. For this reason, a fuel injection nozzle with multiple needle valves for methanol and diesel oil, respectively, in one nozzle body has been developed.

4. TRENDS IN THE DEVELOPMENT OF AMMONIA (NH_3) DF ENGINES

4.1 Low-speed, Two-stroke Ammonia Engines

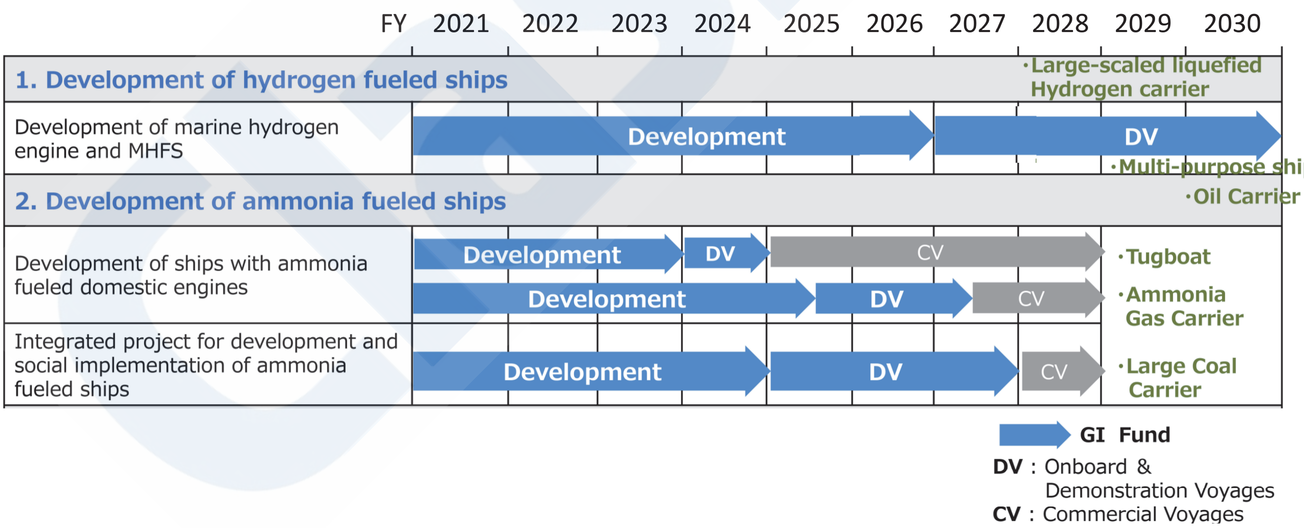


Fig. 4 A part of development schedule of the GI Fund Project for the Development of Next-Generation Ships [13)]

Ammonia-diesel injection types of low-speed, two-stroke main engines are being developed by three licensors, MAN, WinGD and Japan Engine Corporation (J-ENG). Since ammonia has a boiling point of -33 °C at ambient pressure, semi-cooled pressurized type or cooled type tanks are envisaged for onboard liquid storage. When fed into engines, liquid ammonia is further pressurized (according to Mitsui E&S, the line pressure is 8.3 MPa [4)]).

The aforementioned development schedule of the GI Fund is explained using Fig. 4 [13)]. The main engine of the bulk carrier to be built under the “Integrated project for development and social implementation of ammonia-fueled ships,” which is included in "Development of ammonia fueled ships," will be a low-speed, two-stroke ammonia engine, 7S60-LGIA (seven cylinders, cylinder diameter: 600 mm), developed by MAN and built by Mitsui E&S. MAN has completed tests on one cylinder of the test engine (Fig. 5, cylinder diameter: 500 mm) and will conduct tests of all four cylinders burning ammonia.

In ammonia combustion, there has been a concern about emissions of N_2O, a greenhouse gas about 300 times more potent than CO_2. At present (August 2024), none of the above three companies has disclosed confirmed GHG emissions or environmental performance, but MAN has provided qualitative data (Fig. 5) from the one-cylinder test [4], according to which N_2O emissions are reportedly "very low." However, because the unburnt ammonia emissions are higher than expected, reduction by reaction with NOx in the SCR is planned.

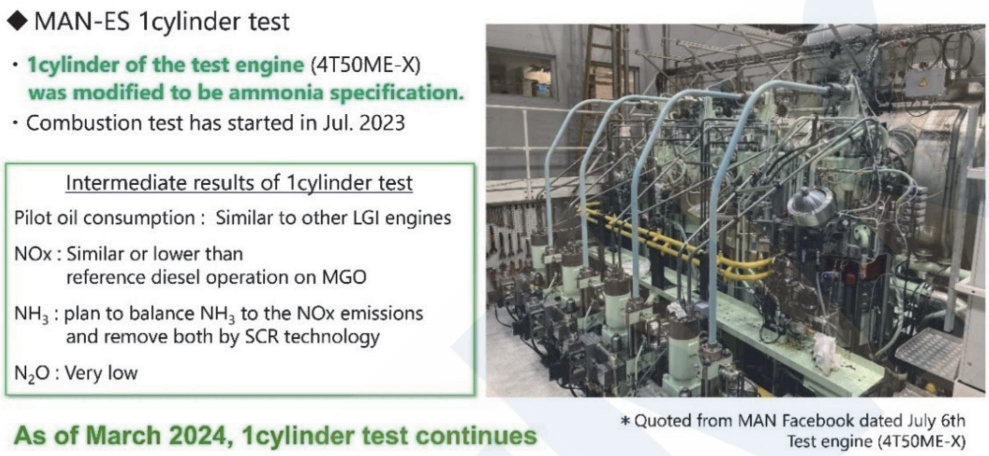


Fig. 5 MAN's one-cylinder ammonia operation test results [4]

Fig. 6 AFMGC: Ammonia-fueled medium gas carrier (projected figure) [14]

Fig. 7 J-ENG's single-cylinder ammonia test engine (left) and ammonia supply system (right) [15]

Next, "Development of ships with ammonia-fueled domestic engines," in Fig. 4 is explained. In December 2023, Nippon Yusen Kabushiki Kaisha (NYK), Japan Engine Corporation (J-ENG), IHI Power Systems Co. and Nihon Shipyard Co., Ltd. signed a series of contracts to construct the world's first ammonia-fueled medium gas carrier (AFMGC) equipped with Japanese-made engines. The four companies have formed a consortium with ClassNK since being selected for the GI Fund project, and full-scale world-leading efforts to develop ships with ammonia-fueled domestic engines are now underway [14].

The background and objectives of the project include the following items:

(1) Contribute to the achievement of net-zero emissions in international shipping.

(2) Establish an ammonia value chain

(3) Strengthen Japan's maritime industry

(4) Establish international rules for the use of ammonia in marine applications.

Fig. 7 shows the single-cylinder engine currently being tested at J-ENG and its ammonia supply system [15]. The company conducted the world's first ammonia co-firing test operation on a low-speed, two-stroke engine.

WinGD is also developing a low-speed, two-stroke ammonia engine using a test engine (Fig. 8) [16] and plans to install the 6X52DF-A engine in the second quarter of 2025 as the main engine of an LPG/ammonia carrier to be built in Korea.

In this connection, Mitsubishi Shipbuilding Co., Ltd. is developing an ammonia fuel supply system and an ammonia treatment system, for which an AiP has been issued by ClassNK (April 2024) [17].

Fig. 8　WinGD's low-speed, two-stroke, single cylinder test engine (cylinder diameter: 520 mm) (courtesy of WinGD)

Fig. 9　A-Tug "Sakigake" (main engine output: 1618 kW x 2 units) [19]

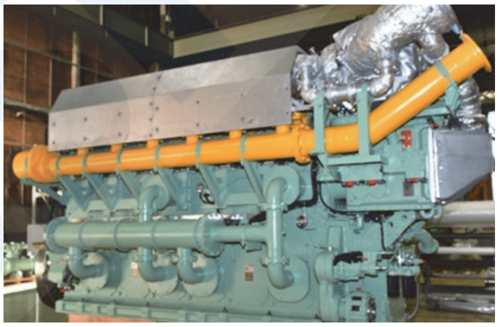


Fig. 10　Medium-speed, four-stroke 28ADF engine for A-Tug (power: 1618 kW/750 rpm/unit, D/S: 280/390 mm, 6 cylinders, Pme: 1.8 MPa) [18]

4.2　Medium-speed, Four-stroke Ammonia Engines

The tugboat for "Development of ships with ammonia-fueled domestic engines" in Fig. 4 is described below. IHI Power Systems has completed a medium-speed, four-stroke ammonia DF engine, which was developed for the main engine of an ammonia-fueled tugboat (Fig. 9: A-Tug). ClassNK issued the world's first classification approval for this engine as an ammonia-fueled marine engine in April 2024 [18]. The engine is currently being fitted to A-Tug, which is engaged in towing operations in Tokyo Bay for a three-month demonstration voyage [19].

This engine is shown in Fig. 10, and is the ammonia Otto cycle type. As with methanol engines of the same type, ammonia is fed into the intake pipe to form a mixture with air. The mixture is compressed by the piston and ignited by pilot diesel oil near TDC. In land-based tests, the fuel-ammonia mixing ratio was gradually increased to achieve a maximum mixing ratio of 95 % (pilot fuel: 5 % of heat). Its N_2O emission is reduced by an after-treatment system, and a GHG reduction rate of more than 90 % is achieved compared to operation with heavy fuel oil.

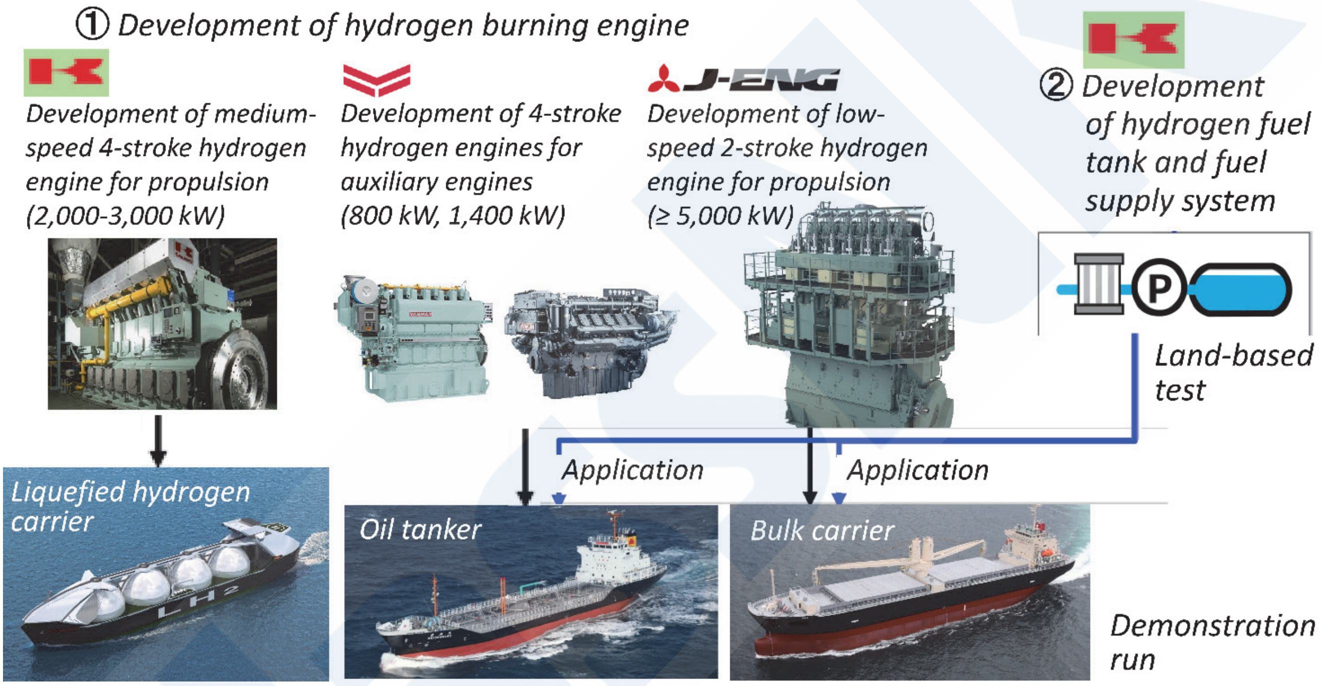
The company has also confirmed the ability to follow load fluctuations required for tugboats and zero ammonia leakage from the actual machine during operation and after shutdown. The company is currently developing an engine (cylinder diameter: 250 mm) for the aforementioned AFMGC's generator.

YANMAR and DAIHATSU DIESEL are also testing ammonia combustion in single-cylinder engines [7), 8)]. Moreover, basic research is being conducted by the both companies with the aim of improving ammonia combustion by co-firing hydrogen. This will become practical once the technology for reforming of the ammonia to hydrogen on board is established.

In Europe, for example, Wartsila has already developed and started release of a W25 type (cylinder diameter: 250 mm) Otto-cycle type ammonia engine [20)]. As an example, the company has presented the provision of a package including parts from ammonia fuel gas supply to the exhaust gas treatment system, as well as a W25 engine, for a Platform Supply Vessel (PSV) retrofit [20)].

5. TRENDS IN THE DEVELOPMENT OF HYDROGEN DF ENGINES

This chapter explains R&D item 1 “Development of marine hydrogen engines and MHFS (Marine Hydrogen Fuel Systems)” in the development schedule of the GI Fund in Fig. 4.



Project Period: FY 2021-FY 2030 (10 years)

Source: Kawasaki Heavy Industries, Ltd., YANMAR POWER TECHNOLOGY CO., LTD. and Japan Engine Corporation

Fig. 11 Development of marine hydrogen engine and MHFS (Marine Hydrogen Fuel System) (NEDO website)

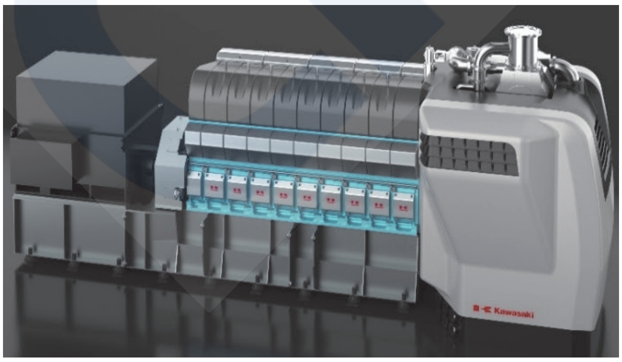


Fig. 12 Hydrogen-fueled DF generator engine (courtesy: Kawasaki Heavy Industries) [22)]

Fig. 13 Hydrogen-fueled multi-purpose vessel (17,500 DWT type) (Rendering) [24)]

Fig. 11 shows an overview of the development of marine hydrogen engines and the Marine Hydrogen Fuel System (MHFS). Kawasaki Heavy Industries' medium-speed, four-stroke hydrogen DF engine (Fig. 12) is scheduled for long-term demonstration as a generator engine of a large liquefied hydrogen carrier, with the aim of developing it as a main engine for propulsion. A basic design approval (AiP) was issued by ClassNK in November 2022 [21].

The hydrogen four-stroke engine in this project is the Otto cycle type, in which hydrogen is supplied at low pressure to the intake port to create a mixture with air. Kawasaki's engine uses exhaust gas recirculation as a technology to suppress abnormal combustion, aiming for a high hydrogen mixing ratio and high power. The hydrogen ratio has already reached 95 % (pilot diesel oil: 5 % of heat), and the output in the hydrogen mode of an eight-cylinder 8L30KG-HDF type (cylinder diameter: 300 mm) is 2.4 MW [22].

The development of four-stroke hydrogen engines as auxiliary engines, as shown in Fig. 11, is under the responsibility of YANMAR. A hydrogen combustion system with diesel micro-pilot ignition has been established through a hydrogen-mixed combustion demonstration test using a single-cylinder engine, and the target has been achieved. Apart from the GI Fund, the company is also developing a high-speed, four-stroke hydrogen engine for a hydrogen-fueled hybrid electric propulsion coastal tanker [23].

In relation to the development of J-ENG's low-speed, two-stroke hydrogen engines in Fig. 11, an AiP was issued by ClassNK in October 2023 for a parcel layout concept for a hydrogen-fueled multi-purpose ship (Fig. 13) by five companies, Mitsui O.S.K. Lines, Ltd., MOL Drybulk Ltd., Onomichi Dockyard Co., Ltd., Kawasaki Heavy Industries, Ltd. and J-ENG [24].

This J-ENG engine is a diesel-cycle type, where hydrogen is injected at high pressure (on the order of 30 MPa) into piston-compressed air. For this reason, Kawasaki developed the MHFS (Marine Hydrogen Fuel System), which supplies high-pressure hydrogen (gas) with less compression work by vaporizing hydrogen pressurized in the liquid phase beforehand. As part of the project, tests of the high-pressure hydrogen injection system are currently in progress by J-ENG, and data on hydrogen embrittlement of engine materials is also being analyzed in collaboration with a research institute [13].

DAIHATSU DIESEL and MITSUI E&S participated in MLIT's “Maritime Industry Intensive Cooperation Promotion Technology Development Support Project” (FY2021-2023) to develop the technology required for a propulsion system for ocean-going ships using hydrogen fuel.

DAIHATSU DIESEL visualized hydrogen combustion as basic research, and started tests using hydrogen supply systems and a single-cylinder engine (Otto cycle type, cylinder diameter: 230 mm, output: 200 kW/900 rpm) from April 2023. As a result, a 96 % GHG reduction (compared to diesel oil) and high output rate equivalent to a natural gas engine could be achieved [25].

MITSUI E&S and its licensor MAN tested hydrogen combustion by modifying one cylinder of the low-speed, two-stroke test engine 4S50ME-T (cylinder diameter: 500 mm, four cylinders, output: 7 MW/117 rpm) [26]. This is a diesel-cycle type based on the ME-GI natural gas engine. A 95 % hydrogen mixing ratio (remaining 5 %: pilot marine diesel oil) at full load operation and a stable combustion state equivalent to those of the other three cylinders operating with marine diesel oil could be obtained, and it was also confirmed that the high-pressure hydrogen required by the engine could be stably supplied from the hydrogen supply system.

In Europe, Wartsila is developing a four-stroke engine and is also working on technology to produce hydrogen from LNG by cracking on board.

A tugboat equipped with two medium-speed hydrogen and gas oil DF engines (power: 2000 kW/set), which was developed by Anglo Belgian Corporation and CMB.TECH, is in operation in the port of Antwerp-Brugge. The tugboat carries compressed hydrogen instead of liquefied hydrogen. In addition, a marine hydrogen mono-fuel engine is being developed [27]. In Japan, JPN H_2YDRO's hydrogen-fueled vessels also use the company's engines [28].

6. SUMMARY

The author described the combustion challenges and solutions for the use of each alternative fuel in the previous paper. This paper has introduced the situation where Dual Fuel engines for marine use are being developed with the challenges solved. Thus, it can be said that engine development has sufficient technological momentum at home and abroad. As mentioned at the outset, issues such as the scale of production of each alternative fuel, supply chain possibilities and costs remain, but it is desirable to perfect the technology, including safety aspects, and to develop human resources who can make use of it, so that they can respond immediately when these issues are resolved.

REFERENCES

1) MLIT website, Mar. 2024. https://www.mlit.go.jp/maritime/maritime_tk7_000048.html
2) ClassNK: My page “Guideline”: Technical Guide for Using Biofuels (Edition 1.1) Apr. 2024.
3) MLIT website, Jan. 2024 https://www.mlit.go.jp/report/press/kaiji07_hh_000302.html
4) MITSUI E&S, Presentation material, 2024.
5) Information of MAN Energy Solutions・CIMAC 2023 Paper No. 523.
6) Information of WinGD: Future Fuel Technology Update, 2024.
7) YANMAR PT, Presentation material, 2024.
8) DAIHATSU DIESEL, Presentation material, 2024.
9) Methanol-Fueled Engine | HANSHIN DIESEL WORKS, LTD. (hanshin-dw.co.jp)
10) AKASAKA Diesels Ltd. website News Release, 24. Jun. 2024.
11) MAN Energy Solutions website: 26. Jul. 2024. & Four-stroke | MAN Energy Solutions (man-es.com)
12) Wartsila website: Wärtsilä Marine Methanol Conversion.
13) NEDO website, Green Innovation, Next-generation Ship Development.
14) ClassNK Press Release 2024/01/25.
15) Japan Engine Corporation, Presentation material, 2024.
16) Information of WinGD, WinGD website: Technical Information Note 035
17) ClassNK Press Release 2024/04/11.
18) ClassNK Press Release 2024/04/08.
19) ClassNK Press Release 2024/08/23.
20) Wartsila website: Wärtsilä 25 Ammonia (wartsila.com) & Press release 26 Aug. 2024.
21) ClassNK Press Release 2022/11/30.
22) Kawasaki Heavy Industries, Presentation material, 2024.
23) ClassNK Press Release 2024/06/19.
24) ClassNK Press Release 2023/10/19.
25) DAIHATSU DIESEL website News, Apr. 2024: https://www.dhtd.co.jp/news/information/2024/pdf/20240408_j2.pdf
26) MITSUI E＆S Group website Press Release, Mar. 2024: https://www.mes.co.jp/press/2024/0307_002399.html
27) CIMAC 2023 Paper No. 203.
28) CMB.TECH | JPNH2YDRO opens Hydrogen Engine R&D Centre in Japan