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Development of 4-stroke medium speed methanol/diesel-fueled engine for marine application in YANMAR

Dual Fuel / Gas / Diesel

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ABSTRACT

YANMAR is conducting research and development on engines that can utilize alternative fuels to fossil based conventional diesel fuels, with the aim of achieving net-zero greenhouse gas emissions by 2050. This paper presents the latest development status of 4-stroke medium-speed diesel-methanol dual fuel engines for marine applications in YANMAR.

Methanol has a higher energy density than hydrogen and ammonia and is liquid phase at room temperature. Therefore, it has a smaller impact on cargo space of vessels and is easy to handle. For these reasons, methanol is a promising fuel for ocean-going vessels. To this background, YANMAR is conducting research and development of a 1 MW-class marine auxiliary engine fueled with methanol with its exhaust gas aftertreatment system.

There are mainly two types of fuel injection systems for methanol-fueled engines: port fuel injection (PFI) and direct fuel injection in cylinder (DI). In PFI, methanol fuel is injected at a relatively low pressure into the intake manifold to form a premixed charge, which is ignited by the pilot diesel fuel injected close to the TDC. In DI, on the other hand, pilot diesel fuel and methanol are injected directly into the cylinder around the TDC, resulting in a form of diffusive combustion. This paper describes the structure and characteristics of each combustion system and discusses its advantages and disadvantages, supported by 3D-CFD and engine experimental data. Directions for selection for different applications and engine sizes are also discussed.

Abnormal combustion, such as knocking, has been found to occur in methanol PFI system, as with LNG (natural gas) and hydrogen. The mechanism will be analyzed, and the effects of the optimization of the air-fuel ratio and fuel injection parameters will be presented, including measures to improve the engine performance.

Since the adoption of methanol-compatible and retrofit engines may be commercialized in the future, the scope of modification of existing engines and the engine system configuration, including the exhaust aftertreatment systems, should be considered. In the case of DI, high pressure methanol is used, which is expected to increase the complexity of the methanol supply system and can increase the CAPEX.

When considering the spread of methanol as a fuel for marine engines, there is a need for a dual-fuel (DF) engines that can also be operated with diesel fuel. YANMAR believes this is also true for hydrogen and ammonia, and we plan to develop a methanol-fueled 4-stroke medium-speed engine of the DF type. There is also a viewpoint of ensuring redundancy for new fuels.

1 INTRODUCTION

YANMAR group is taking on the challenge to be an “ecological footprint-free, GHG (Green House Gas)-free corporation based on recycled resources,” and is moving forward with the introduction of green powertrains to the market in order to achieve carbon neutrality by 2050 [1]. Under such circumstances, we are engaged in all-out research and development of next-generation fuel technologies in line with the “zero GHG emissions by 2050,” a strategy set forth by the IMO (International Maritime Organization) for marine engines.

There are two major paths for green powertrains: one is conversion from conventional fossil fuel to alternative fuels, another is electrification. Figure 1 shows the forecast in which alternative fuel types and powertrains are expected to be applied to each type of vessels, based on the cruising range and the capacity of the powertrains. Hydrogen, ammonia, methanol and biodiesel fuel as alternative fuels might be applied for long or middle range vessels, while electrification technologies for vehicles such as fuel cells or large batteries may be applied for the operating range close to land side.

Methanol stands out in Figure 1 here for three reasons: (1) it is a liquid fuel, thus easy to handle and conventional onboard equipment can be utilized, (2) its relatively higher volumetric energy density minimizes the impact on cargo space, and (3) it is relatively less hazardous than ammonia in the event of a leakage. Because of these low hurdles to introduction, methanol has attracted attention as an alternative fuel, especially for ocean-going vessels. The IMO's target of 5-10% use of zero-emission fuels by 2030 can be one of the reasons behind this trend. The low hurdles to adoption are not limited to new shipbuilding, but also work to the advantage of retrofitting or methanol-ready vessels. Considering this situation, YANMAR POWER TECHNOLOGY CO., LTD. (YPT) is prioritizing the development of medium speed methanol-fueled marine generator engines among other engines fueled with different alternative fuels.

While methanol is attracting attention in the short term, ammonia and hydrogen are also seen as promising alternative fuels in the medium to long term, and capital investment in infrastructure development for each of these fuels is expected to be increase. In addition to this, the marine industry is demanding safe and reliable operation of engines, and trust in diesel engines is high because of its long track record. Therefore, we believe that dual-fuel (DF) engines, which combine the environmental performance of the alternative fuels with the redundancy of diesel back-up operation, will be effective, so already announced to use the DF type for the marine methanol-fueled 4-stroke medium-speed engines that YPT plans to develop in near future.

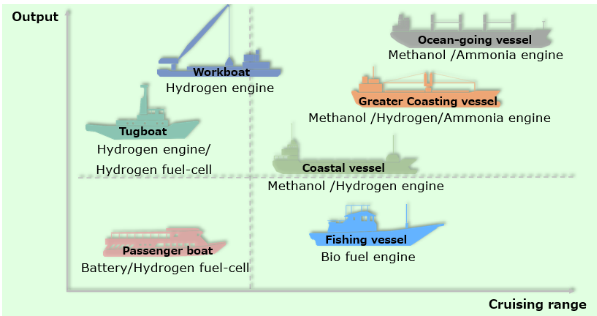
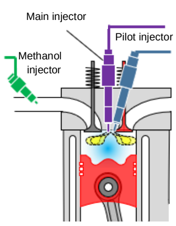
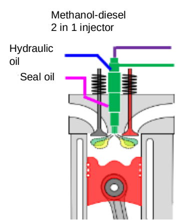


Figure 1. Power trains for each type of vessels.

2 CONCEPT STUDY FOR METHANOL ENGINE

There are two major types of fuel injection system for methanol-fueled engines: Port fuel injection (PFI) and direct fuel injection into cylinder (DI). In the PFI system, methanol fuel is injected with a relatively low pressure into the intake port during the intake process to form a fuel-air premixture. The pilot fuel injected near top dead center (TDC) is used as an ignition source. In DI system, on the other hand, pilot fuel and methanol fuel are injected directly into the cylinder (with appropriate timing) around TDC, resulting in diffusive combustion [2][3]. This paper details the structure and characteristics of each system, and contrasts Pros and Cons using 3D-CFD simulation analysis and various experimental data. In addition, its selection guidelines for different applications and engine sizes are discussed.

Table 1. Schematic diagram of two methanol injection systems.

Injection system	PFI	DI
Main component		
Combustion process	Flame propagation	Diffusive combustion

2.1 PFI system

Experiments were conducted using a small-bore single-cylinder engine (SCE) in order to understand the basic combustion and emission characteristics of a methanol/diesel mix combustion engine. Table 2 shows the engine specifications used in this experiment. An FT-IR type exhaust gas analyzer (BEX2000-FT, Best Sokki) was used to analyze the components of the exhaust gas. The engine operating load was defined as the indicated mean effective pressure (IMEP), and the methanol and diesel oil feed rates were adjusted to maintain a constant IMEP of 1.0 MPa. The mixing ratio of methanol and diesel oil was defined by the energetic ratio, the lower heating value (LHV) of 43.3 [MJ/kg] for diesel oil and 19.9 [MJ/kg] for methanol were used. The excess air ratio, i.e. intake air flow rate was adjusted by changing the manifold air pressure which was controlled by external air compressor pressure.

Table 2. Engine specifications.

Number of cylinders	1
Bore [mm]	94
Stroke [mm]	110
Displacement [L]	0.76
Number of valves	4
Speed [min^{-1}]	1200
IMEP [MPa]	1.0

The in-cylinder pressure and rate of heat release obtained under fixed diesel injection timing that is assumed mechanical fuel injection equipment are shown in Figure 2 and representative performance data is shown in Figure 3. Figure 2 shows that the ignition delay becomes longer and the combustion phasing trends to retard as the methanol mixing ratio increases. This can be attributed to the prolonged physical ignition delay due to the lower compression end pressure and temperature caused by the higher latent heat of methanol vaporization and the longer chemical ignition delay of methanol [4].

Operation at a methanol mixing ratio of 70% or higher was difficult because of pre-ignition. This is owing to the higher residual gas temperature due to later combustion phasing, resulting in auto-ignition of the methanol-air premixture before ignition of pilot diesel fuel. The thermal efficiency in Figure 3 showed an increasing trend up to 45% methanol mixing ratio, but it decreased over 45% methanol mixing ratio. Figure 2 shows that the increase in the maximum cylinder pressure and the shortening of the combustion duration contribute to the increase in the thermal efficiency at 45% methanol mixing ratio. On the other hand, at 70% methanol mixing ratio, the thermal efficiency decreased due to the retarded combustion phasing, and NO_X emission also increased up to 45% methanol mixing ratio and then showed a tendency to decrease at 70% methanol mixing ratio. Unburned methanol and formaldehyde emissions increased with increasing methanol mixing ratio. The unburned methanol can be caused by the wall film formed in the intake port and the crevice volume of combustion chamber. Formaldehyde is an intermediate product in methanol combustion and may be emitted from low-temperature areas such as near walls or crevices, where the combustion reaction is frozen midway.

Because vaporization process follows the "d^2 equation" as equation (1), and K_b is a function of temperature, thermal conductivity, density and specific heat at constant pressure, it is important for emission reduction to be smaller initial droplet diameter and higher intake air temperature to promote methanol vaporization [5].

$$d^2 = d^2_0 - K_b t \qquad (1)$$

Where:
- d: current droplet diameter [m]
- d_0: initial droplet diameter [m]
- K_b: evaporation rate constant [m^2/sec]
- t: elapsed time [sec]

According to the above results, the combustion and emission characteristics of diesel/methanol mix combustion in a PFI system are well understood, and indicate that the challenges are pre-ignition, increased emissions of unburned methanol and formaldehyde at higher methanol mixing ratios.

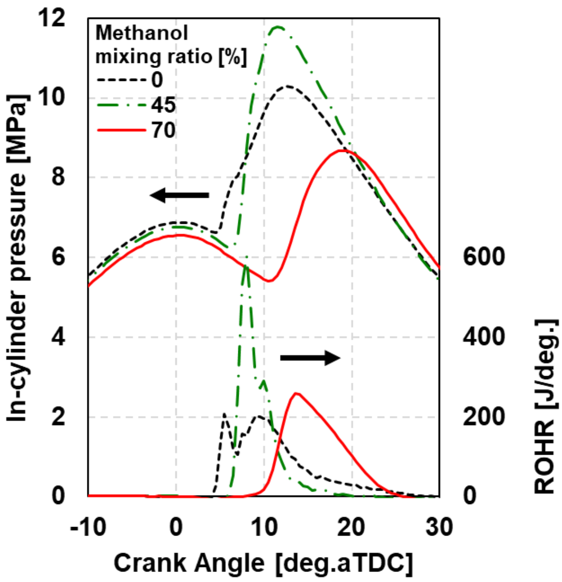


Figure 2. In-cylinder pressure and heat release rate under different methanol mixing ratio with fixed diesel injection timing.

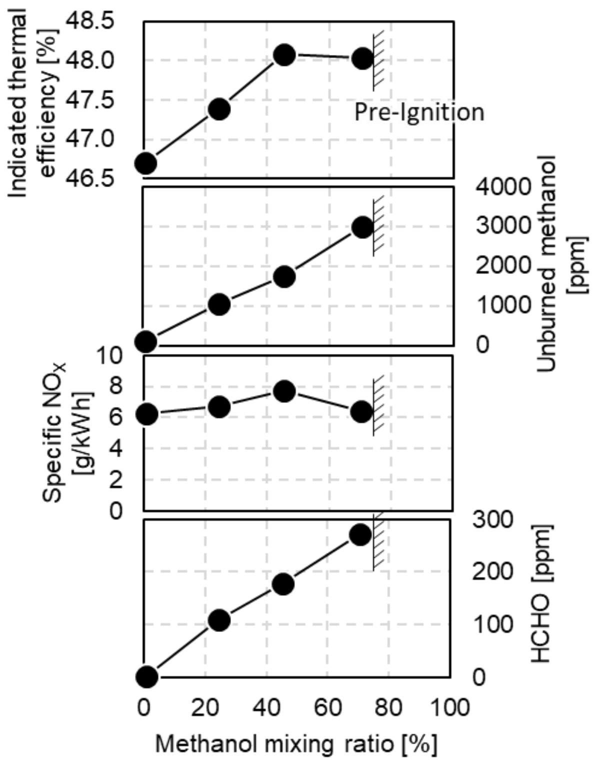


Figure 3. Performance data and emission characteristics for various methanol mixing ratio with fixed diesel injection timing.

Methanol mixing ratio can be further increased by optimizing diesel pilot injection. For example, the addition of pre-injection can advance the combustion phasing and prevent pre-ignition. An example of the indicator diagram with close to 90% methanol mixing ratio by adopting variable diesel injection timing (assuming common rail type micro-pilot injection system) is shown in Figure 4.

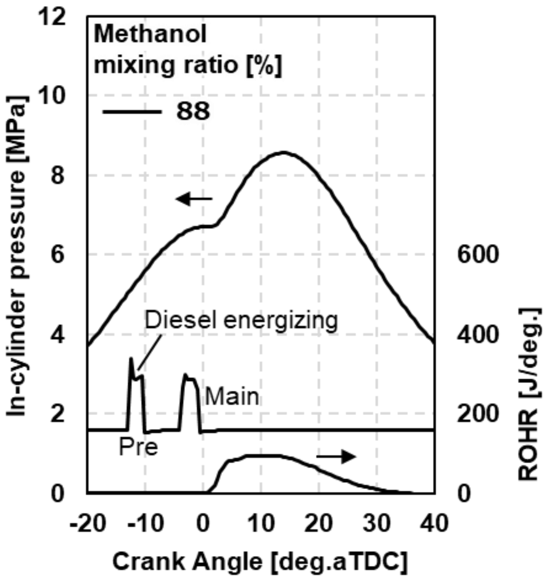


Figure 4. In-cylinder pressure and heat release rate with optimised diesel injection strategy.

2.2 DI system

Next, the basic combustion and exhaust characteristics of the DI system were experimentally investigated. A SCE with the specifications shown in Table 3 was used for the experiment. Methanol is boosted to 60 MPa by a dedicated pump installed at facility side, then supplied to the injector and injected directly into the cylinder at an arbitrary timing. The methanol and diesel oil have different flow paths and can be injected at independent injection pressure, timing, and duration. The methanol injected directly into the cylinder is ignited by the diffusive flame of the pilot diesel oil and forms diffusive combustion.

Figure 5 shows the performance data of DI system. The maximum methanol mixing ratio reached 96%, indicating that the stable operation equivalent to diesel engine is possible. Indicated thermal efficiency showed improved from the base diesel while the NO_X emission was lower than those of original diesel in entire load range. NO_X reduction may be attributed to the lower combustion temperature around the methanol flame due to the latent heat of methanol vaporization injected directly into the cylinder, and the lower adiabatic flame temperature of methanol compared to diesel fuel oil.

The above results provide insight into the combustion and emission characteristics of the DI system, and at the same time, experimentally clarify its stable combustion at high methanol mixing ratio and lower emissions compared to the PFI system. On the other hand, there are unburned methanol emissions that are harmful to human health and that emissions tend to increase at low loads, thereby after-treatment devices might be necessary to purify unburned methanol.

Table 3. Engine specification and experimental conditions for methanol DI system.

Number of cylinders	1
Bore [mm]	220
Stroke [mm]	320
Displacement [L]	12.16
Number of valves	4
Rated speed [min^{-1}]	900
Rated power [MPa]	IMEP=2.73

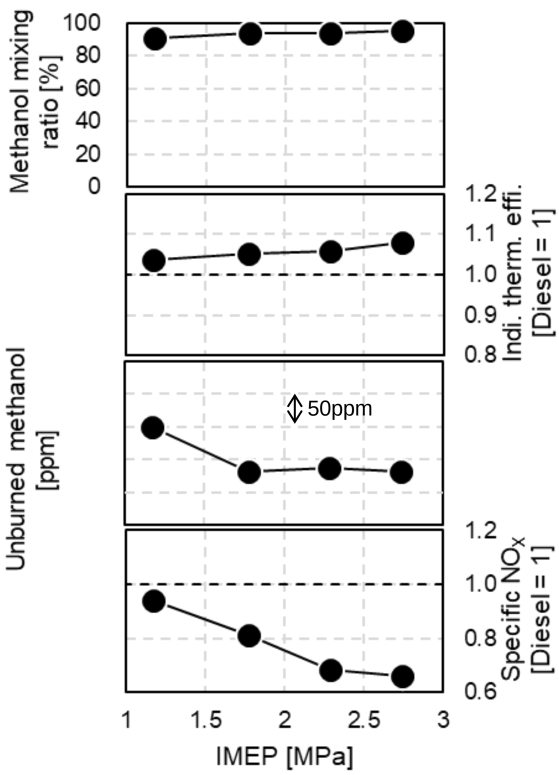


Figure 5. Initial performance data of methanol DI system at SCE testing.

2.3 YPT's direction of system selection for methanol fueled engine

Based on the results of studies described in the previous sections, the possible selection policy for each application are as follows:

- Methanol-ready, retrofit capability

PFI is the better choice because of its simplicity as an engine system. DI requires a methanol booster pump, piping to withstand that pressure, injector hydraulic oil and sealing oil supply apparatus as auxiliary equipment. However, it is necessary for PFI system to consider the after-treatment system, as described later in Section 3.2, in order to deal with exhaust emissions.

- Propulsion Engine

Relatively higher power output compared to generator engines, in other word, higher fuel consumption, can maximize methanol usage with a DI that has a high mixing ratio in the entire load range. In addition, the risk of abnormal combustion is low because of the diffusive combustion system, and redundancy against sudden load changes is high. On the other hand, the impact of auxiliary equipment mentioned earlier on the hull design and additional cost must be carefully discussed.

- Small bore engines

In case of many additional equipment, such as DI, the challenge is how to place them around the cylinder head of engine. In this respect, PFI, which basically requires only the addition of a methanol injector to the intake port, is suitable for small bore engines.

3 DEVELOPMENT OF METHANOL MEDIUM SPEED DF ENGINE

As the shift to alternative fuels progresses, YPT expects that gaseous fuels such as ammonia, and hydrogen will be applied less case for relatively small ocean-going vessels, such as handy-size bulk carriers, due to the footprint of their fuel storage spaces and relating supply systems. One of the prospections also mentioned that Methanol engine seems to be used in bulkers and tankers [6]. In other words, methanol-fueled engines among alternative fuels are likely to be the main choice for the 1 MW-class generator engines used in those vessels.

YPT is developing a methanol-fueled engine (shown in Figure 7) based on the 6EY18ALWS diesel engine (shown in Table 4), which has an established reputation for use in bulkers and tankers, match with the market demands, and has completed initial evaluations. This section introduces the status of this effort and discusses prospects.

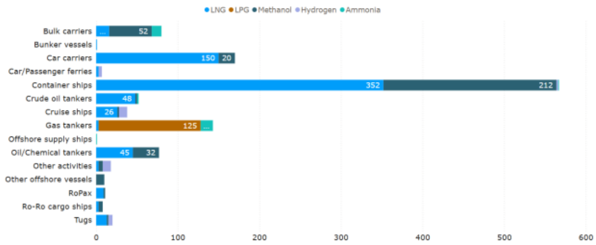


Figure 6. Prospection for alternative fuel uptake by ship type [6].

3.1 Engine design

Based on the selection policy described in the previous chapter, PFI system was selected as the combustion system because of its advantages for small bore and generator engine. The ease of methanol-ready or retrofit service is also a deciding factor. In addition, as mentioned earlier, DF type engine is decided to be applied. The engine control system such as cylinder pressure monitoring and protection devices is based on our proven DF engine for liquified natural gas to ensure redundancy [7]. The modifications to the methanol engine include replacing the gas admission valve installed on the intake port with a methanol injector. Pilot ignition with a conventional mechanical diesel injector is also the feature of the small-bore engines. Such a minimum modification will contribute to a quick launch to the market because of the proven reliability of base engine and short development lead-time.

Figure 7. Conceptional image of methanol engine.

Table 4. Engine specifications.

Number of cylinders	6
Bore [mm]	180
Stroke [mm]	280
Rated speed [min^{-1}]	900
Rated BMEP [MPa]	2.50

For stable operation in methanol mode, it is essential to control the air excess ratio within an appropriate range to avoid knocking, which is caused by auto-ignition of methanol-air premixture, and misfiring, which is caused by an excessively lean mixture. The adjustable range of the excess air ratio has been investigated in advance using 1D-simulation with reference to the experimental result that is mentioned in Section 2.2, and the feasibility of exhaust gas temperature, maximum pressure in the cylinder, and capacity of the excess air ratio control device have been investigated.

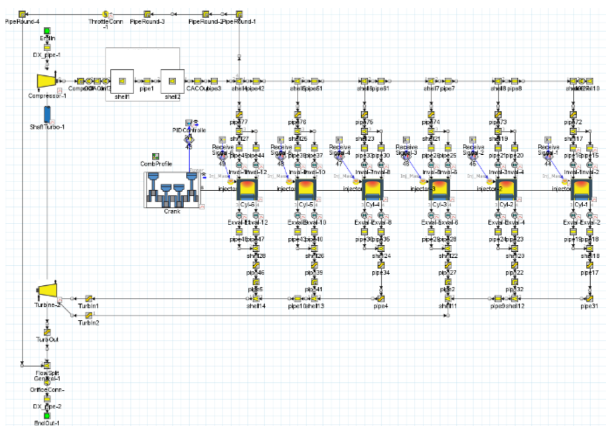


Figure 8. Example of 1D-simulation model.

To reduce emissions with methanol PFI system, it is important to promote the mixing of air and methanol in the cylinder and minimize wall film formation on the intake port. 3D-CFD, such as with Frossling model based on equation (1) is used to calculate the evaporation process, is useful for elucidating these phenomena and optimizing the methanol injection position. Figure 9 shows CFD results of the initial and the improved designs of the PFI injector layout. In the initial design, the methanol fuel was biased towards one of the intake ports, resulting in a significant amount of methanol wall film. Based on the CFD results of the initial design, a detailed analysis of the airflow and methanol spray within the intake port was conducted, then improved the position and orientation of the methanol injector. The improved design is shown on the right side of Figure 9. In this improved design, the methanol fuel is evenly distributed to both intake ports compared to the initial design. This affect to reduce the unburned methanol approximately 30% against initial position (see Figure 10). This campaign will be continued to optimize the specifications of the methanol injector, aiming to minimize the amount of wall film and to promote the mixing of air and methanol fuel in the combustion chamber.

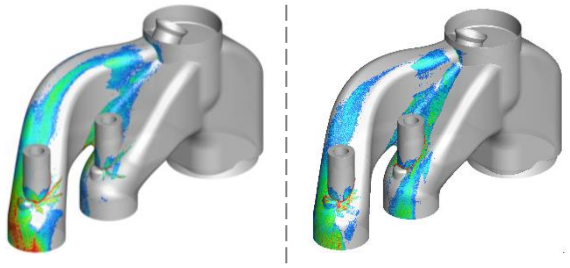


Figure 9. Optimization of the position of methanol PFI injector using 3D-CFD (left: initial proposal, right: improved).

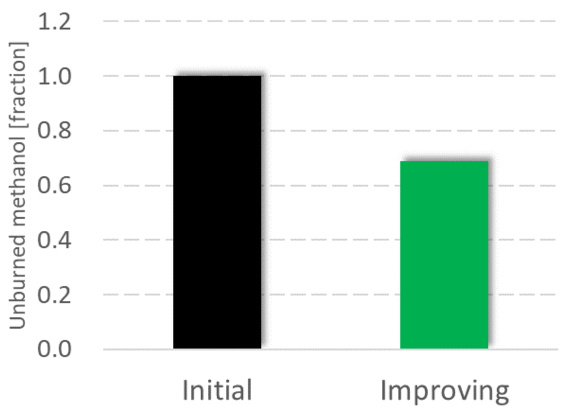


Figure 10. Experimental result of injector position which affects unburned methanol emissions.

3.2 After-treatment system

Exhaust emission from methanol-fueled engines contains unburned methanol and formaldehyde [8]. These components combine with NH_3 derived from the urea, which is injected in SCR system, to form toxic hydrogen cyanide [9]. There are no regulations for methanol, formaldehyde and hydrogen cyanide as of today, but they are harmful to human health, so YPT is considering to adopting oxidation catalyst to minimize these components.

Figure 11 shows the test results of decomposition of unburned methanol. In this test, a small piece of catalyst (φ1" x L50mm) was used and tested under conditions simulating exhaust components and gas flow rates as the inlet mixing gas. Experimental results showed that the methanol decomposition rate reached almost 100% at temperatures much lower than the actual engine operating temperature range. From this result, the practical performance of the catalyst is sufficient for purification of methanol engine exhaust gases.

On the other hand, sulfur content of the marine diesel fuel can cause sulfur poisoning of the oxidation catalyst, resulting in performance deterioration. Figure 11 also shows a comparison of decomposition performance with and without sulfur coexistence. The influence of sulfur on the performance was observed, especially low temperature zone, but it was not significant in the operating temperature range, and it was confirmed that methanol and formaldehyde can be decomposed without any problems even in the coexistence of sulfur.

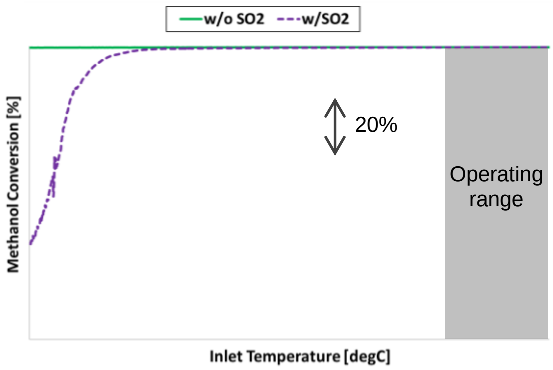


Figure 11. Methanol decomposition performance of oxidation catalyst.

Note that since unburned methanol and formaldehyde themselves do not affect reduction performance of NO_X by conventional SCR system for diesel engines, it can be used without any design changes. Although a more compact design can be expected since NO_X emissions are reduced in the methanol mode, the conventional size must be maintained since the diesel mode must be used as a backup.

4 CONCLUSIONS

In this paper, Methanol-fueled engine was discussed and reached the conclusion below.

A stepwise but secure transition to carbon-neutral society is required in the marine industry today, YPT expects that methanol will play a major role in that movement. Methanol-fueled DF engines are also expected to be redundant and responsive to fuel supply uncertainties.

There are two combustion systems for methanol-fueled engines, each with its own Pros and Cons was discussed in this paper. YPT decided to apply PFI system as first step because our main target is small-bore, 1MW-class marine generator engines, and that has advantage for methanol-ready vessel, plans to brush-up the system and launch it in 2026.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

IMEP	Indicated Mean Effective Pressure
BMEP	Break Mean Effective Pressure
COV	Co-efficient of Variant
DF	Dual Fuel
DI	Direct Injection in cylinder
GHG	Green House Gas
IMO	International Maritime Organization
LHV	Lower Heating Value
LNG	Liquified Natural Gas
PFI	Port Fuel Injection
SCE	Single Cylinder Engine
SCR	Selective Catalytic Reduction
TDC	Top Dead Center
YPT	Yanmar Power Technology co., ltd.

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