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Methanol Dual Fuel Engine Development Status

Dual Fuel / Gas / Diesel

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ABSTRACT

Currently, countries around the world are working to reduce greenhouse gas (GHG) emissions from various industries. Ships are no exception.

One way to reduce GHG emissions is to use methanol, ammonia, or hydrogen as fuel instead of fuel oil.
Here, methanol can be made carbon neutral by using green methanol, which is obtained by using CO2 and hydrogen derived from renewable energy sources.
It is a liquid at room temperature and pressure, and although toxic, it is relatively easy to handle, and demand for it is rapidly increasing on ships, especially large container ships.

In light of this situation, we are also developing a dual-fuel engine that can use methanol.
When liquid methanol is used, there are two possible fuel injection systems.

One method is injection into the air intake port (PI), and the other is direct injection (DI) into the cylinder.
In the case of PI, the advantage is that the fuel is supplied at relatively low pressure (~60 bar) and the system can be simplified.
On the other hand, since the combustion mode is premixed combustion, it is necessary to deal with abnormal combustion such as knocking.

In addition, methanol injected in liquid form flows into the cylinder while vaporizing, but some of the methanol may not vaporize and flow into the cylinder in liquid form.
In such cases, stable combustion becomes difficult and week fire or miss fire may occur.
As a result, the rate of methanol co-combustion will be limited.

On the other hand, in the case of DI, injection is performed at high pressure (approximately 600 bar) into the cylinder. The combustion mode is diffusion combustion as in the current diesel engines.
Since it is injected into the cylinder at high temperature and high pressure, it vaporizes quickly after spraying. Combustion then proceeds with the ignition fuel oil.

Therefore, unlike PI, the mixing ratio can be high. Also, because of diffusion combustion, there is almost no need to consider abnormal combustion such as knocking.
However, a system to boost the pressure of methanol to high pressure is required. In addition, because diesel fuel is required for backup, it is necessary to develop injectors that are compatible with both diesel fuel and methanol fuel.
Therefore, the level of development difficulty is much higher than that of PI.

In this paper, we will introduce the development status of methanol DF engines, especially those using the DI method.

1 INTRODUCTION

Efforts are currently underway around the world to reduce greenhouse gas (GHG) emissions from various industries.

Ships are no exception, and Figure 1 shows the GHG reduction strategy adopted at IMO_MEPC80 in 2023, with enhanced targets compared to the 2018 adoption, including clear targets for the 2030 and 2040 phases.

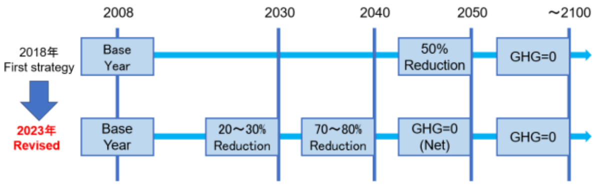

Figure 1 GHG reduction load map

Therefore, a rapid response to GHG emission reductions is needed on board ships.

One of the ways to reduce GHGs is to use methanol, ammonia and hydrogen as fuels instead of conventional diesel fuel.

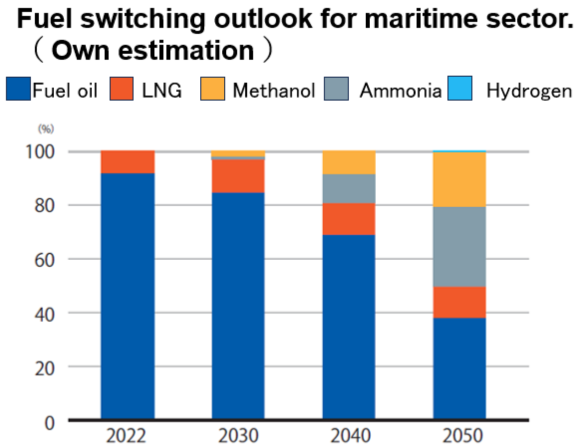

Figure 2. Fuel switching outlook for maritime sector

Figure 2 shows our own prediction of the future penetration rate of alternative fuels. Methanol is expected to spread in the market ahead of ammonia. We believe that the share of ammonia will eventually exceed that of methanol, but not until after 2040.

Furthermore, methanol can be made carbon neutral by using green methanol, which is obtained by using CO_2 and hydrogen from renewable energy sources.

It is also liquid at ambient temperature and pressure, and although toxic, it is relatively easy to handle, so demand is spreading rapidly among ships, especially large container ships.

In this paper, we present the methanol-fuelled engine under development.

2 DEVELOPMENT OVERVIEW

2.1 Base Engine Model selection

The methanol engine was planned to be developed as a Dual fuel (DF) engine based on the existing diesel engine. Figure 3 shows the diesel engine on which it is based.

The DE series is our latest diesel engine portfolio, with bore diameter sizes ranging from 185-330 mm. In recent years, the number of containers that require power, such as reefer containers, has tended to increase for large container vessels, so they require more power than tankers and bulk carriers.

Therefore, the DE-33 with a bore diameter of ø 330 mm was chosen as the base model for the methanol DF engine. The reason is that the engine covers the power requirements of large container ships, and the base diesel model has already been shipped in several hundred units and is highly regarded in the market.

Figure 3. “DE” Diesel engine series.

2.2 Methanol fuel injection / combustion characteristics strategy.

Direct injection (DI) was adopted as the fuel injection method for methanol fuel. The reasons are as follows.

・In general, the larger the bore diameter, the worse the abnormal combustion characteristics, such as end-gas knock, in premixed combustion systems.

・Good performance can also be expected in important characteristics of engines for power generation, such as load pick-up characteristics.

・The MFR should be as high as possible in order to reduce CO_2 emissions.

The MFR is defined here as follows.

$$MFR = Cm \;/\; Ctot \cdots Eq.(1)$$

MFR : *Methanol Fuel Ratio for a given output condition.*

Cm : *Calorific value of consumed methanol for a given output condition.*

$Ctot$: *Total calorific value (methanol + diesel fuel) for a given output condition.*

Next, the technical content is presented.

3 TECHNICAL TASK AND APPROACH

3.1 General

The technical challenges in the development of a DI-based methanol DF engine are as follows.

1. Development of a methanol high-pressure fuel injection system.
2. Development of a methanol leak detection system.
3. Verification of combustion performance.

Details on each Item are presented from the next section.

3.2 High pressure methanol fuel system development

3.2.1 High pressure methanol pump

In order to inject the required amount of methanol in a suitable injection period, it is necessary to increase the pressure to several hundreds of bar.

The pump is of plunger type and is driven by an electric motor. The motor uses variable speed control via an inverter to change the discharge flow rate to obtain the required fuel pressure.

Figure 4 shows a known examples of the placement of high-pressure pumps on board. According to the Marine classification, pumps etc. are supposed to be located in the fuel preparation room on the hull.

In this case, the fuel preparation room itself is a secondary barrier, so that methanol leakage due to a single failure is permitted. [1]

The pressurized methanol is supplied to the engine through the double wall piping.

Double wall piping is required as essential in Marine classification to prevent fuel splashing into the engine room in the event of a single failure. [1]

Therefore, double wall piping on the hull requires a design pressure of several hundred bar and is often welded in the hull due to work restrictions. This increases the risk of leakage due to welding defects and so on.

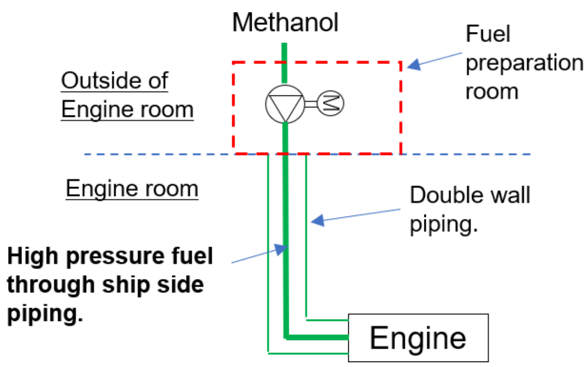

Figure 4. High pressure pump arrangement.

In order to facilitate the installation of double wall piping on the hull, we considered mounting the pump on the engine and carried out the following modifications.

1. No external methanol leakage due to a single failure.
2. Appropriate detection methods in the event of a methanol leak.

For item No. 1, the design of the sealing section was revised to prevent methanol leakage from the pump.

For item No. 2, in the event of a methanol leak, the design is such that methanol is directed into a passages where a leak detection device is installed.

3.2.2 Methanol / diesel fuel injector

Dual fuel injector capable of injecting methanol and diesel fuels is presented. Figure 5 shows an image of the injector.

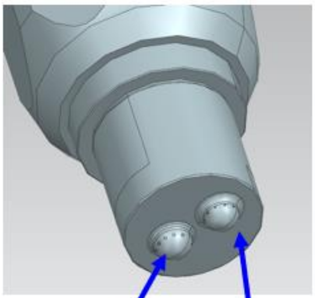

Figure 5. Dual Fuel Injector design

Methanol is injected into the combustion chamber at any time from the Methanol nozzle by means of a Solenoid vavle fitted to the injector and externally supplied Control oil.

Diesel fuel mode or pilot diesel fuel in Methanol fuel mode is supplied by a jerk-type pump and injected into the combustion chamber through a diesel nozzle.

3.2.3 High pressure lubricating oil pump

As the lubricating oil required to control the injectors and for sealing internally must be higher than the methanol fuel pressure, we considered using a plunger-type pump used in diesel common rail systems.

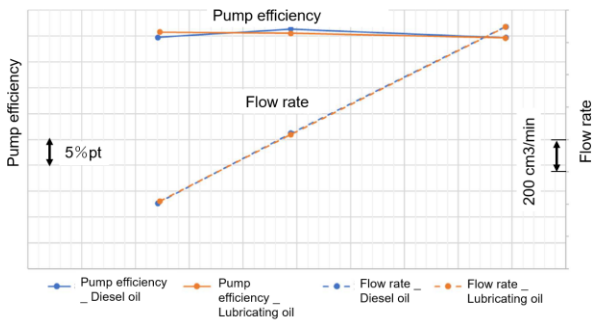

Figure 6. Lubricating oil pump characteristics.

Figure 6 shows the measured pump efficiency and flow characteristics for diesel oil and lubricating oil, and as no differences in flow characteristics were observed, the diesel common rail pump was used as the high-pressure pump for Sealing & Control oil.

3.3 Methanol leak detection system

Table 1 gives an example of the design requirements required by the Marine classification when Liquid Natural Gas (LNG) and methanol are used as fuels. Methanol is liquid at ambient temperature and pressure, so a liquid detection sensor for leak detection is mandatory.

Table 1. Comparison of Rule requirement

Fuel	Class	Book title	Example of requirement
LNG	Class NK	Rules for the survey and constructions of steel ships	･Double wall piping ･**Gas detector** for leaked Gas
	DNV	Part6 Chapter 2 section 5	
Methanol	Class NK	Guidelines for Ships Using Alternative Fuels	･Double wall piping ･**Liquid detector** for leaked Methanol
	DNV	Part6 Chapter 2 section 6	

In addition, the methanol fuel piping in the engine room is double wall piping and the empty space between the inner and outer pipes (hereafter referred to as ‘sleeve space’) is required to be treated in one of the following two cases. [1]

1, Air ventilation and detect evaporated methanol with a gas detector.

2, Filled with inert gas (inerting). Detects in gas pressure.

So, in combination with the design requirements described in Table 1, the combination of detection equipment required is as follows.

Case1：Liquid and gas detection sensors.

Case2：Liquid detection sensors and pressure sensors.

Figure 7 shows an example of the double wall piping required to realise the Case 1 and Case 2 structures.

In Case 1, it is necessary to secure a sufficient area of sleeve space to provide the required amount of ventilation and to reduce the pressure loss during passage. If the pressure loss is large, the ventilation system becomes larger, which is a disadvantage for the hull’s installation arrangement. On the other hand, if the area is secured, the size of the double wall piping may become larger.

In Case 2, there is no need to increase the area of the sleeve space. Therefore, the same design as the diesel common rail pipe as shown can be applied and a compact design is possible.

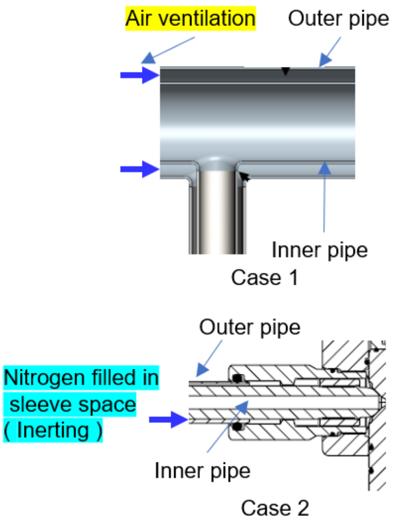

Figure 7.Double wall pipe comparison

However, if methanol leaks into the sleeve space, the pressure is expected to increase due to the closed space. The design pressure of the double wall piping outer pipe should be designed at the maximum pressure that can be expected, as required by the maine classfication. [1]

Therefore, a suitable safety device, such as a safety valve, must be provided in the Sleeve space to prevent excessive pressure increases.

For this reason, 1D simulations were carried out to estimate the pressure increase in the sleeve space.

Figure 8 shows the results. The simulation software used was GT-SUITE from Gamma Technologies, USA.

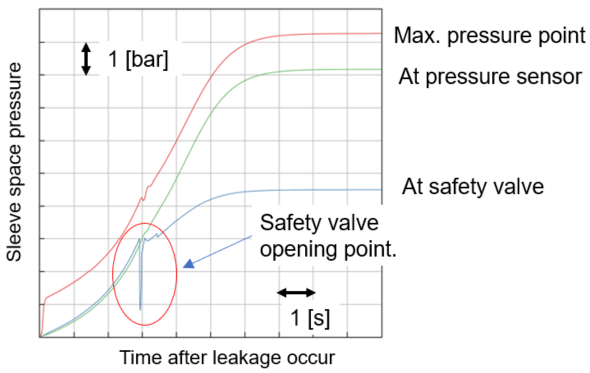

Figure 8. 1D simulation result example

The maximum pressure in the Sleeve space is near where the methanol leak occurs.

In this example, the pressure rises to the pressure at which the safety valve opens in 3 seconds after the leakage occurs.

The pressure in the sleeve space settles 7 seconds after the leakage occurs. It was found that the settling pressure depends mainly on the size of the leakage area and the flow coefficient of the safety valve.

From the results obtained, the appropriate design pressure for the double wall piping outer pipe and the specification of the safety valve were determined, so Case 2 was chosen as it is easier to handle high pressure and has a simpler design.

An interface unit has also been developed for the supply and discharge of methanol fuel to and from the hull, as well as for the detection and handling of leaked methanol.

It integrates a number of functions such as pressure sensor, liquid detector, safety valve, and relief valve.

3.4 Verification of Combustion Performance

3.4.1 SCE testing

In order to verify the combustion performance in advance, a single cylinder engine (SCE) of similar engine size was used to understand the combustion characteristics. Table 2 shows an example of the SCE used in the advanced tests and the test conditions. Note that the advance study employed a common rail system not only on the methanol side but also on the diesel side.

Table 2. SCE specification

Bore [mm]	285
Stroke [mm]	390
Engine speed [min-1]	720
BMEP [MPa]	～2.4
Methanol fuel pressure [bar]	～600
Air excess ration (λ)	～3

An example of a test result is given from the next section.

3.4.2 Test result

3.4.2.1 Start of Methanol Injection variation

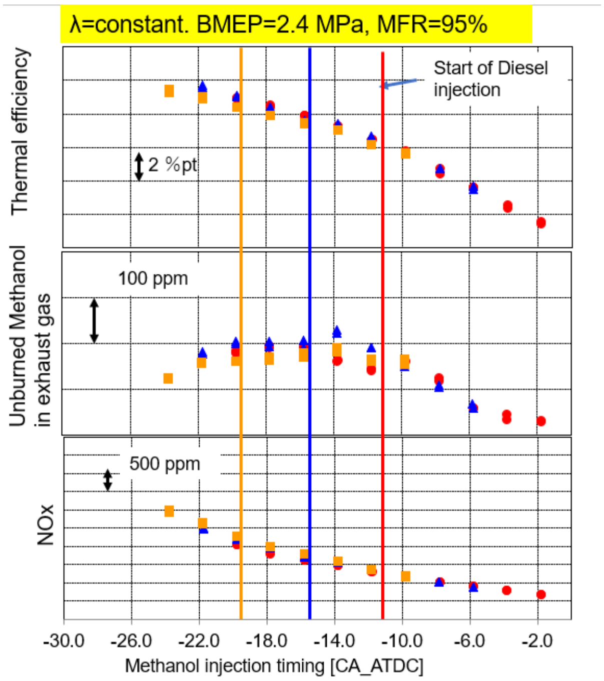

Figure 9. Performance related to emissions and thermal efficiency.

Figure 9 shows the thermal efficiency and the methanol concentration in the exhaust gas. The horizontal axis shows Start of Methanol Injection (SMI). The vertical line in the diagram shows the Start of Diesel Injection (SDI). That is, to the left of the vertical line indicates that methanol injection is earlier than diesel fuel.

Thermal efficiency is independent of SDI and increases with SMI on the advance side. The concentration of unburnt methanol in the exhaust gas was found to decrease when the SMI was significantly on the retard timing.

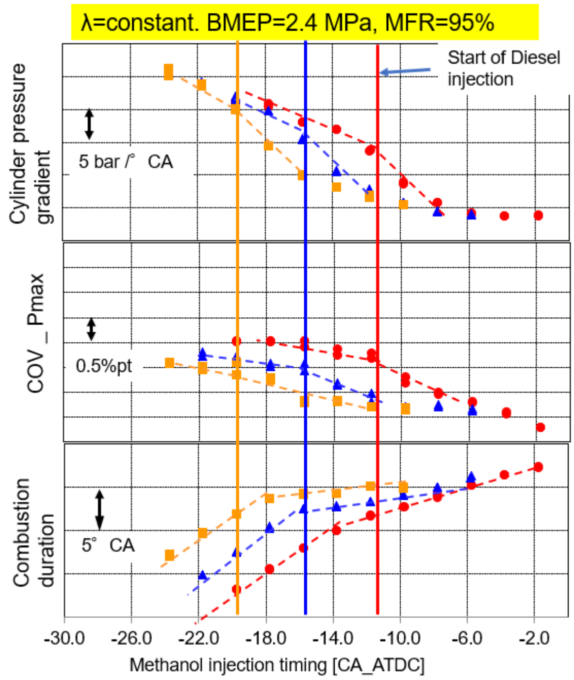

Figure 10. Performance related to combustion fluctuations.

The combustion variance and combustion duration are then shown in Figure 10. Here the definitions of Coefficient of Variance _ Pmax (COV _ Pmax) and combustion duration are as follows.

COV_Pmax

=Pmax standard deviation / Averaged Pmax ・・・*Eq.(2)*

Combustion duration = *90% MFB [°CA]*− *10% MFB [°CA]* ・・・*Eq.(3)*

MFB・・・*Mass Fraction Burn*

These results show that the combustion duration rapidly shortens when the SMI is earlier than the SDI.

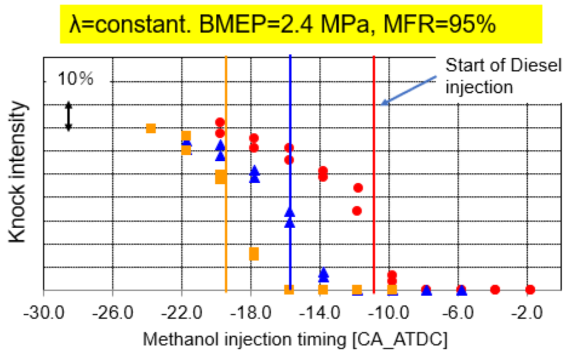

Figure 11. Knock intensity characteristics

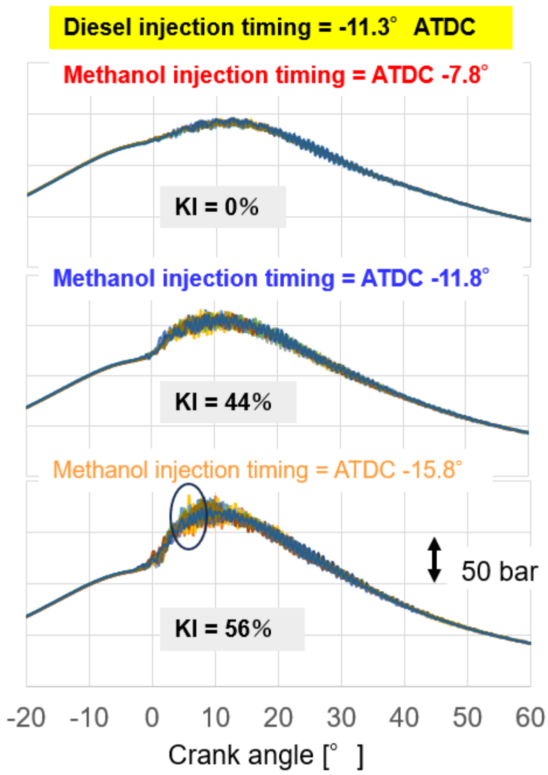

Figure 12. Cylinder pressure curves

Figure 11 shows a comparison of Knock intensity , which is an FFT analysis against the cylinder pressure to ascertain the assumed abnormal combustion frequency band.

Next, band pass filter (BPF) processing of the assumed abnormal combustion frequency band is performed on the cylinder pressure during a given crank angle period, and the resulting amplitude value of the cylinder pressure is determined by the frequency at which it exceeds a specified value. Here, the BPF was set at 1-3 kHz.

If the SMI is earlier than or the same timing as the SDI, the knock intensity increases significantly.

On the other hand, if the SMI is later than the SDI, there is no increase in knock intensity.

Figure 12 shows the results of the multiple-cycle overlay of the cylinder pressure curves; it can be seen that the amplitude of the pressure increases as the SMI is advanced. Spike-like pressure increases were also observed in the circled areas.

It is assumed that when the SMI is advanced, the proportion of the mixture that is locally premixed increases and combustion occurs rapidly after ignition, resulting in combustion with oscillations.

This is assumed to have resulted in the shortened combustion period shown in Figure 10.

From the point of view of engine protection, excessive combustion oscillations should be avoided. Since the aspect of end-gas knock is different from that of premixed gas engines, it is necessary to examine more deeply whether such combustion is acceptable or not.

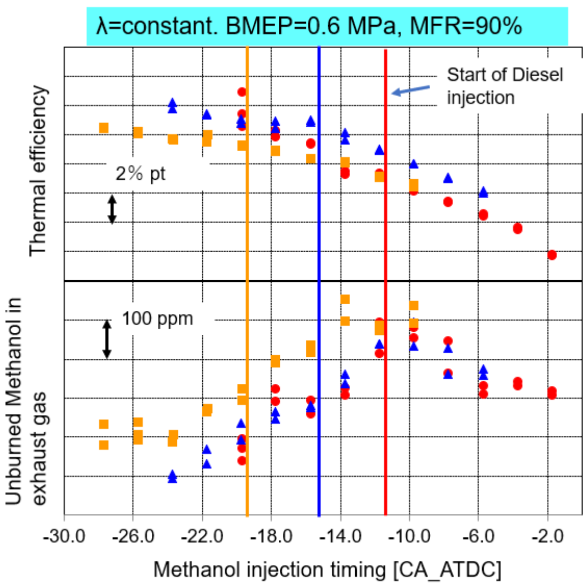

Figure 13. Performance related to emissions and thermal efficiency.

Next, the trend at low load is shown in Figure 13. The thermal efficiency increases with the advance of SMI, which is the same as in high load, but the thermal efficiency decreased when the SDI was advanced too much.

This is assumed to be due to the fact that the low load and advanced timing had a negative impact on the ignition performance of the diesel fuel. Unburnt methanol showed the same trend as high load.

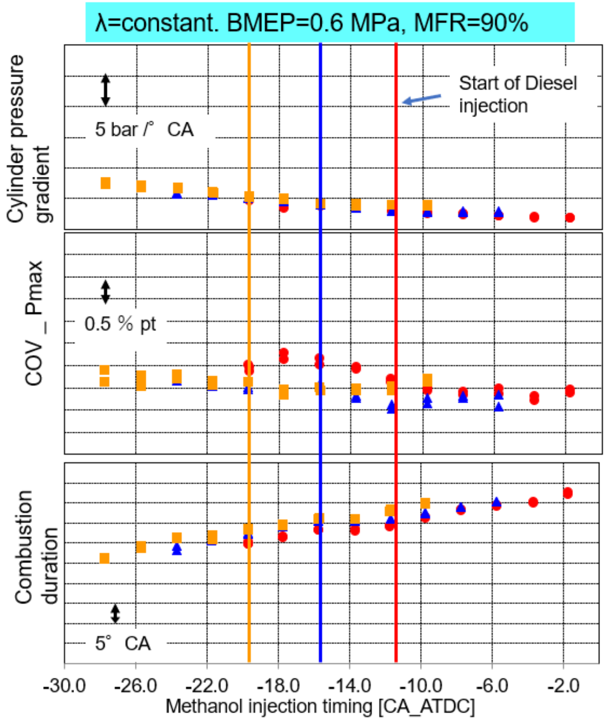

Figure 14. Performance related to combustion fluctuations.

Figure 14 shows the combustion fluctuations and duration at low load and Figure 15 shows the knock characteristics. In addition, no significant increase in knock intensity was observed when the SMI was advanced.

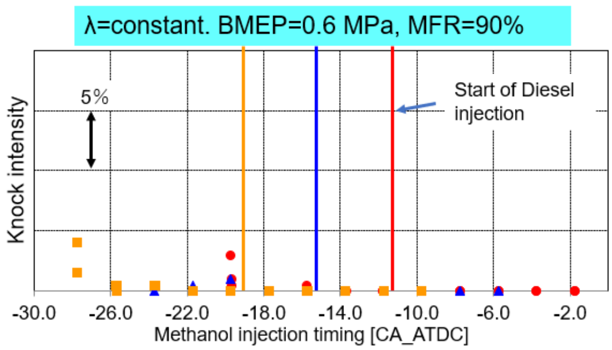

Figure 15. knock intensity characteristics

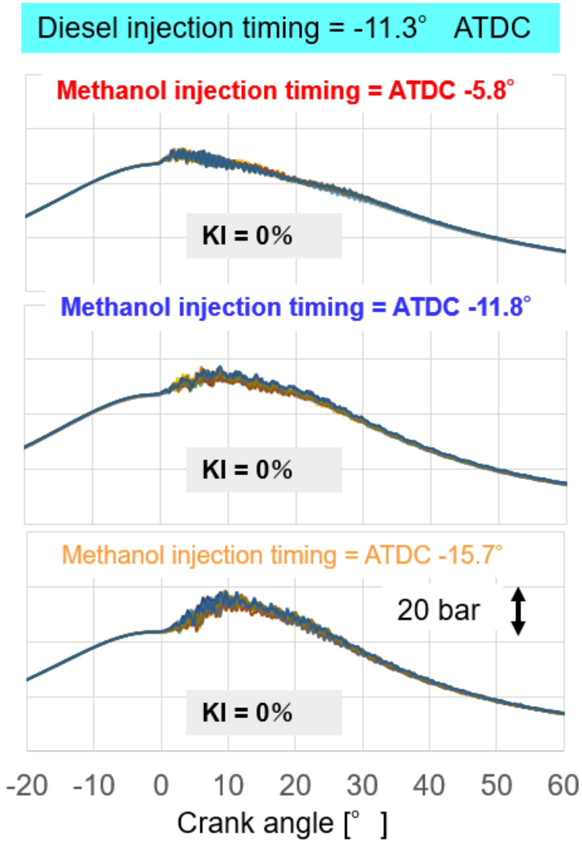

Figure 16. Cylinder pressure curves

Figure 16 shows the cylinder pressure at low load: the cylinder pressure amplitude tends to increase slightly with SMI advance angle, but no change was observed at higher loads.

3.4.2.2 λ variation

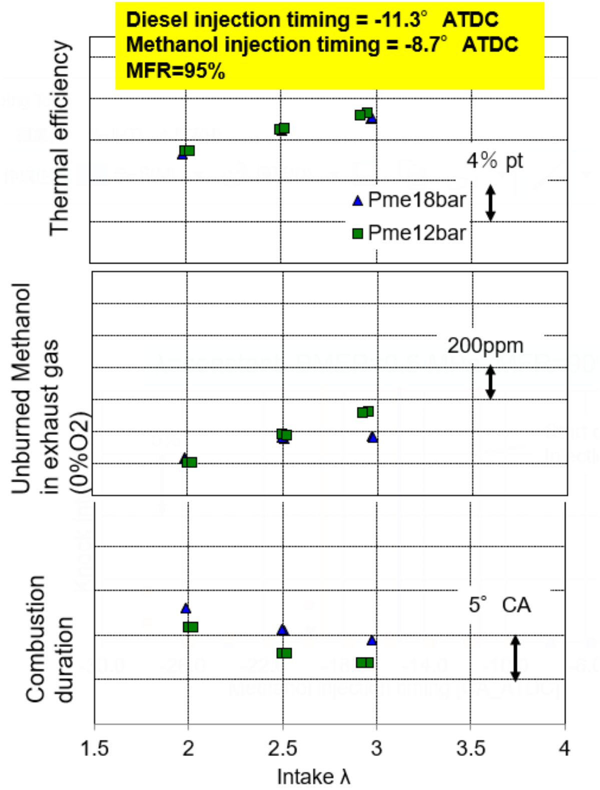

Figure 17. Performance characteristics relative to λ variation

The results of the λ change are then shown in Figure 17. Thermal efficiency, combustion duration and COV_Pmax all showed better characteristics on the lean side. On the other hand, unbuned methanol showed an increasing trend.

The reasons for this are estimated as follows. Diesel fuel is injected before methanol, and methanol injection occurs in the area where the diesel fuel has auto-ignited.

Therefore, if λ is excessively lean, the initial combustion on the diesel side gets worse and the temperature rise in the combustion field becomes slower. When methanol is injected there, the oxygen necessary for combustion is present, but the ambient temperature is low and combustion is slow, resulting in unburned methanol.

On the other hand, combustion continues, so the temperature field rises further. Therefore, methanol injected after the initial combustion is injected into the rising temperature field, resulting in rapid combustion and a shorter combustion duration.

These results confirm that stable combustion is possible at the same level of λ as in diesel fuel mode. In other words, there is no need to significantly change the air-fuel ratio control between diesel and methanol modes.

3.4.2.3 Methanol fuel pressure variation

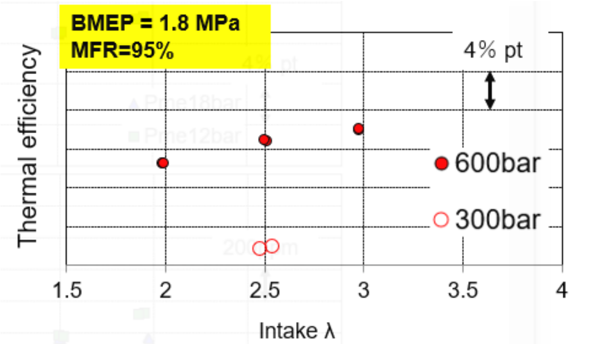

Figure 18. Performance characteristics at different fuel pressure

Figure 18 shows the change in thermal efficiency with varying methanol fuel pressure. The advantage of a low fuel pressure is that the design pressure of the double wall piping on the hull can be reduced when the methanol high-pressure pump is installed on the hull.

In particular, 300 bar is the pressure used in MAN's ME-GI engine, the main engine for LNG-DF vessels [2]. Therefore, as shipyards have a lot of experience in the construction of double wall pipes, stable quality can be expected.

However, it was observed that the thermal efficiency decreased significantly when the fuel pressure was reduced. The main reason for this is considered to be the significantly increased fuel injection duration.

To shorten the fuel injection duration when fuel pressure is low, the total area of the injector holes needs to be increased. However, it should be noted that expanding the total area may increase the size of the injector nozzle tip and even the injector size itself.

4 NEXT STEP

Based on the results obtained so far, a Multi Cylinder Engine (MCE) has been designed. Combustion tests are underway using an SCE with a bore diameter of ø330. Figure 19 shows SCE photographs, Figure 20 shows the MCE model outline, and Table 3 shows MCE specification.

Figure 19. Bore 330mm SCE

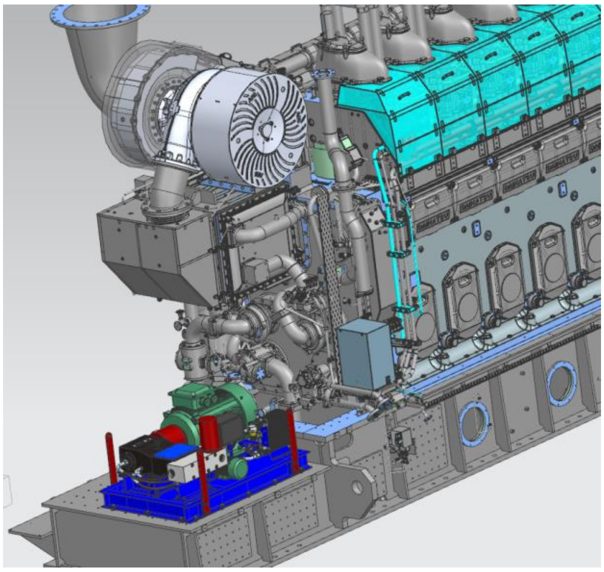

Figure 20. MCE design example

Table 3 MCE specification

Bore [mm]	330	
Stroke [mm]	440	
Engine speed [min-1]	720	
Cylinder quantity	8	6
Engine output [MW]	～4.8	～3.6
Fuel	Methanol, MDO, HFO	

MCE will start testing in early 2025 to establish diesel and methanol performance, adapt various controls, and how to respond to methanol leaks.

5 CONCLUSION

We are developing a methanol DF engine for large container ships. We have adopted direct in-cylinder injection (DI) as our fuel injection system.

The technical challenges in the development of a DI-based methanol DF engine are as follows.

1. Development of a methanol high-pressure fuel injection system.

2. Development of a methanol leak detection system.

3. Verification of combustion performance.

For Item No 1, a pump has been developed that does not leak externally in the event of a single failure. This is because the pump is mounted on the engine.

In the known method, the pump has to be installed on the hull side, but it is difficult to install double wall piping on the hull side to cope with the high pressure.

For Item No 2, for the double wall piping, a structure similar to that of a diesel common rail was adopted, which allows a compact design.

Next, to meet the leak detection requirements of the marine classification, a pressure monitoring method between the double wall outer pipe and the inner pipe and a direct detection method for liquid methanol were adopted.

In addition, the design pressure of the double wall outer piping was studied using GT-SUITE, including the requirements for safety valves to prevent excessive pressure build-up.

For Item No 3, a combustion test was carried out using a bore diameter of 285 SCE.

The results obtained as follows.

1. Earlier SMI is above the SDI, higher thermal efficiency and shorter combustion period, etc., but cylinder pressure curve is accompanied by high-frequency oscillations. This is particularly likely to occur under high load conditions.

2. Leaner λ, shorter combustion period and better thermal efficiency. On the other hand, unburnt methanol was increased.

3. Low methanol fuel pressure increases the injection period and significantly worsens thermal efficiency.

6 DEFINITIONS

ATDC: After Top Dead Center
BPF: Band Pass Filter
BMEP: Break Mean Effective Pressure
COV: Coefficient
CA: Crank Angle
DF: Dual Fuel
DI: Direct Injection of Variation
FFT: Fast Fourier Transform
GHG: Greenhouse gas
KI: Knock Intensity
LNG: Liquid Natural Gas
MFR: Methanol Fuel Ratio
MFB: Mass Fraction Burn
MCE: Multi Cylinder Engine
Pmax: Peak Cylinder Pressure
SCE: Single Cylinder Engine
SMI: Start of Methanol Injection
SDI: Start of Diesel Injection
λ : Air Excess Ratio

7 REFERENCE

[1] Class NK, Guidelines for ships using Alternative Fuels.

[2] “High pressure fuel gas supply system for ME-GI” Journal of the JIME Vol. 51, No.1 (2016)