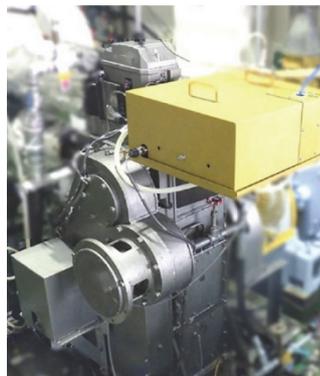


Development of a Low-Cost Methanol-Diesel Dual-Fuel Engine Contributing to the Decarbonization of Ships



TAKAYUKI YAMAMOTO*¹ TOMOHIRO KOGA*²

TOMOHIRO TAKAHASHI*² TAKAFUMI TANAKA*³

RYOSUKE KOGURE*³ RYOSUKE TAKAGI*³

Toward achieving a low-carbon/carbon-neutral society, Mitsubishi Heavy Industries, Ltd. is promoting the development of a methanol-diesel dual-fuel engine with a view to introducing it as a marine main or auxiliary engine. Among the carbon-neutral fuels, methanol is easier to handle than hydrogen or ammonia. While being a promising alternative fuel for marine vessels, methanol poses technological challenges of coping with combustion fluctuations and minimizing unburned methanol emissions. Using diesel pilot ignition for the combustion system, CFD analysis was conducted to optimize the formation of the fuel-air mixture and investigate the combustion behavior in detail. A single-cylinder test unit was used to verify the effect of combustion control; the results confirmed that the issues of combustion fluctuation and unburned methanol emission can be considerably mitigated. By developing these findings into a multi-cylinder unit for practical use, we aim to help make a carbon-neutral society a reality.

1. Introduction

As part of the global movement toward carbon neutrality, the shipping sector has been making active efforts to reduce greenhouse gas (hereinafter referred to as GHG) emissions. Especially, introducing carbon-neutral fuel to propulsion drive/auxiliary engines can be a critical step for this purpose. Among such carbon-neutral fuel candidates, including ammonia and hydrogen, methanol stands out owing to its properties of taking a liquid state under ordinary temperature and pressure, having a high energy density, and being relatively easy to handle. Methanol was thus the first to enter the demonstration stage as an alternative marine fuel in the market. When burned, methanol emits less CO₂ than fossil fuels. If e-methanol or bio-methanol, in particular, is used as a fuel, CO₂ emissions are regarded as virtually zero. According to a report by the Nippon Kaiji Kyokai (ClassNK), a total of 62 methanol-fueled ships, whose gross tonnage (GT) is 5,000 or more, were in service as of June 2025. The figure is expected to rise in the years to come⁽³⁾. Mitsubishi Heavy Industries, Ltd. (hereinafter referred to as MHI) is focusing on the development of a methanol-diesel dual-fuel engine that ignites methanol with diesel. This report presents the progress made in the development of combustion technology using a single-cylinder test unit and CFD analysis.

2. Overview of methanol-diesel dual-fuel engine

Table 1 shows the physical properties of fossil fuels and alternative fuels including methanol. Unlike hydrogen and ammonia, methanol is liquid under ordinary temperature and pressure, which is advantageous because no extra energy is required for liquefaction, and by being less toxic than ammonia, its handling is easier. This serves as a tailwind for the promotion of its wide application. However, because of its low cetane number, methanol as a fuel has difficulty self-igniting. Ignition is usually forced using an ignition source. Of the two ignition methods (i.e., spark ignition and pilot diesel ignition), the latter is more commonly adopted among the

*1 Research Manager, Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

*2 Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

*3 Energy Engineering Department, Engine & Energy Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.

methanol-fueled engines in marine vessels. MHI's engine development also focuses on this pilot diesel ignition method (**Figure 1**). The ignition mechanism starts with the injection of methanol into the intake port to form a methanol-air mixture. This mixture is then fed to the combustion chamber before being compressed by a piston to a state of high temperature and high pressure, to which diesel is injected. The diesel spontaneously ignites and the flame triggers the combustion of the methanol-air premixture. The advantage of this ignition method lies in the highly flexible operability that allows the engine to run only on diesel as well. As adapting the existing diesel engine to dual-fuel operation with methanol requires only the addition of a methanol injection system, retrofitting can be less costly. On the other hand, appropriate combustion conditions have to be set up to ignite and burn two types of fuels (i.e., methanol and diesel) in a stable manner. The verification is under way using CFD analysis and a single-cylinder test unit.

Table 1 Comparison of fuel physical properties

	Gasoline	Diesel	Hydrogen	Ammonia	Methanol
Physical state (under ordinary temperature and pressure)	Liquid	Liquid	Gas	Gas	Liquid
Density (liquid) (kg/m ³)	750	850	71 at -253°C	682 at -33°C	792
Lower heating value (MJ/kg)	43.1	43.2	120	18.6	19.7
Boiling point (°C)	35-180	240-350	-253	-33	65
Latent heat of vaporization (kJ/kg)	290-380	250-300	N/A	N/A	1100
Cetane number	N/A	40-55	N/A	N/A	3

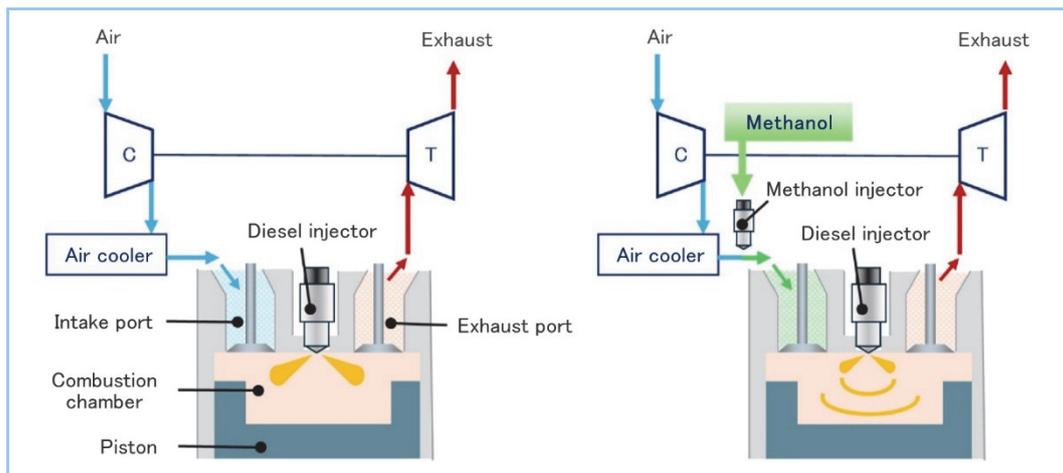


Figure 1 Methanol-diesel dual-fuel engine system

3. Technological challenges to methanol dual-fuel engines

The technological challenges, which are the key to the development of methanol dual-fuel engines, are to control fluctuations in combustion and minimize unburned methanol emissions. Methanol has a high latent heat of vaporization. When injected and vaporized in the intake port, methanol absorbs heat from the charge air. Methanol in the fuel-air mixture also has the effect of slowing down the diesel reaction rate. It therefore gets more difficult to ignite diesel than in the case of fueling with diesel only, and the combustion tends to be unstable. If the injected methanol is deposited onto the wall surface of the intake port before it vaporizes, the amount of methanol supplied to the combustion chamber varies with each cycle. This amplifies the fluctuation in combustion, which leads to more and more cycles having weak combustion. The consequent incomplete combustion results in increased emissions of unburned methanol. This tendency gets more pronounced as the ratio of methanol to diesel increases. Enabling proper combustion to occur at a higher methanol ratio and effectively reducing GHG emissions necessitates optimizing the parameters related to the formation of fuel-air mixture and combustion conditions, such as methanol injection, diesel injection, air excess ratio and intake air temperature. Combustion thus has to be stabilized.

4. Use of CFD to develop a methanol-diesel dual-fuel technology

CFD analysis is used to optimize the specifications in relation to the formation of fuel-air mixture and combustion conditions. For the development of a methanol dual-fuel engine, flow characteristics and combustion behavior are investigated in detail by CFD analysis. The results lay the foundations for design guidelines on stable combustion. CFD is applied to either mixing flow analysis or combustion analysis, depending on the purpose. Individual research examples of each analysis are as follows:

- (1) Examples of mixing flow analysis (non-combustion analysis)
 - Formation of homogeneous fuel-air mixture in the combustion chamber
 - Inhibition of methanol deposition onto the wall surface of the intake port
 - Prevention of methanol blow-through during intake and exhaust valve overlap
- (2) Examples of combustion analysis
 - Prediction of cycle-to-cycle combustion fluctuations and consideration of countermeasures
 - Optimization of combustion control parameters (e.g., air excess ratio, injection timing, and charge air temperature)
 - Verification of measures to improve the thermal efficiency and exhaust gas properties

As mentioned earlier, combustion fluctuates as the methanol substitution ratio gets higher. It is therefore important to take necessary measures to increase the substitution ratio. The causes of combustion fluctuation include cycle-to-cycle variations, for example, in the amount of methanol supplied to the combustion chamber, or in the concentration distribution of fuel-air mixture in the combustion chamber. Just observing the methanol injection conditions gives quite a few influencing factors such as methanol injector nozzle specifications (e.g., nozzle diameter, number of nozzles, and direction of injection) and injection conditions (e.g., injection timing, pressure and duration). Their optimization has to be achieved by trial and error. MHI makes full use of CFD analysis instead of going through an overwhelmingly large number of testing processes required for optimization.

Figure 2 is an example of analyzing the methanol concentration distribution in the cylinder during the intake process, with the aim of considering the specifications of the methanol injector nozzle. The after-the-improvement results reflect both the changes in the direction of methanol injected into the intake port from the injector and the adjustments for distribution/timing of methanol passing through the two intake valves. As visualized in the figure, the methanol concentration is distributed more evenly than the before-the-improvement results. Consequently, the concentration distribution varies less from cycle to cycle, so can be expected to produce a suppressing effect on the combustion fluctuation. Non-combustion analysis is utilized here to check the mixing state of air and methanol. Having a lower computational load than combustion analysis (presented below), it primarily aims to narrow down the range of injector specifications by examining the methanol concentration distribution in the cylinder and the amount of methanol deposited onto the wall surface of the intake port. This is an effective step that can lead to the combustion analysis presented below.

Figure 3 shows an example of the combustion analysis that predicts cycle-to-cycle variations of the in-cylinder pressure and heat release rate. In this analysis, the actual engine cycle of four strokes (intake, compression, expansion and exhaust) was faithfully reproduced. The computation was performed for multiple consecutive cycles, thereby enabling the prediction of combustion fluctuation in an actual engine. The after-the-improvement results reflect the adjustments to various parameters such as methanol injection pressure, nozzle diameter, injection duration and location, and charge air temperature. As shown in the figure, the cycle-to-cycle variations were reduced from those of before-the-improvement, in terms of both in-cylinder pressure and heat release rate. Thus, CFD-based desk review makes it possible to predict combustion fluctuations before engine parts are prototyped. MHI is therefore promoting the use of this method for short-term development.

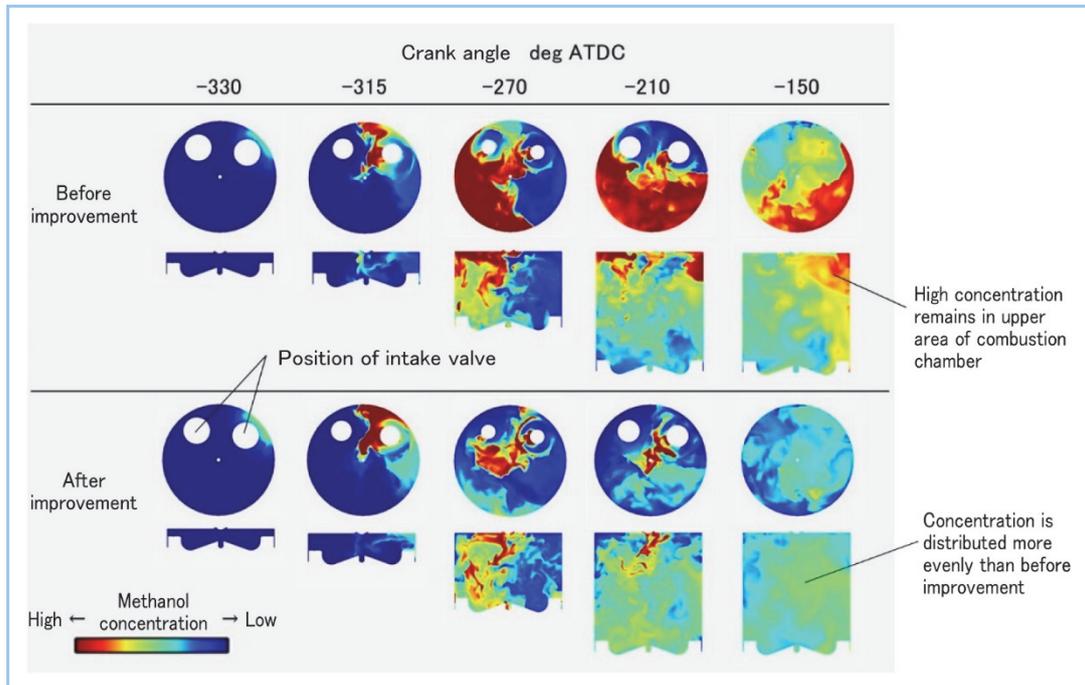


Figure 2 CFD analysis results: the predicted distribution of methanol concentration in the cylinder

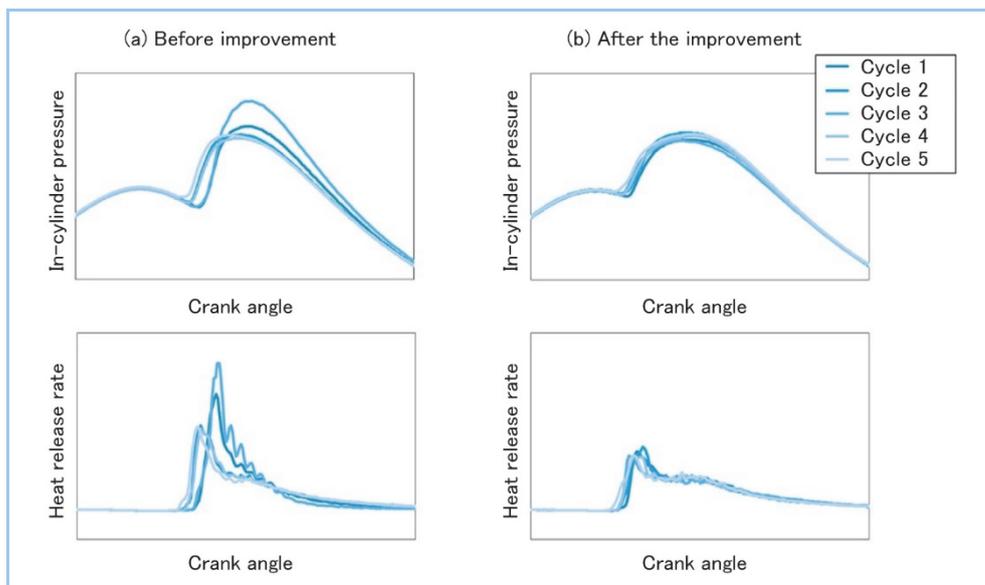


Figure 3 CFD analysis results: prediction of cycle-to-cycle variations in in-cylinder pressure and heat release rate

5. Combustion test using a single-cylinder test unit

The characteristics of methanol combustion are understood using a single-cylinder test unit, as shown in **Figure 4**. This test unit is designed to have the same cylinder bore as MHI's main product model SR series. The parts used for verification can be directly applied to the actual multi-cylinder SR series without scaling up.

Figure 5 compares diesel fueling and methanol dual fueling in terms of the in-cylinder pressure and heat release rate. Unlike diesel fueling, methanol dual fueling showed a long delay in ignition. The combustion variability of each cycle was also amplified, which led to the increased emissions of unburned methanol. **Figure 6** gives the verification results of the effects of controlling the air excess ratio, diesel injection timing and charge air temperature as means of mitigating combustion fluctuation and unburned methanol emission. In the figure, "no control" means no conditions were changed from the SR series diesel engines (based on which a new model will be developed), while "with control" indicates that some changes were made to adapt to methanol dual fueling. Their comparison of the results shows that significantly large effects were produced by

controlling the air excess ratio and diesel injection timing in accordance with the methanol combustion characteristics. Both combustion fluctuation and unburned methanol emission were greatly alleviated. On the other hand, no such direct outcomes were observed at higher charge air temperatures. However, as ignition occurred earlier, raising the charge air temperature can be an effective measure to reduce the risk of misfiring due to delayed ignition during methanol dual fueling. Based on these findings, a control system for the actual unit is currently being developed. Prototyping of the methanol injector, which was verified by CFD analysis, is under way. The verification will be conducted using a single-cylinder test unit before applying it to the SR series multiple-cylinder engines. In this way, practical application of a methanol-diesel dual-fuel engine will be attempted.

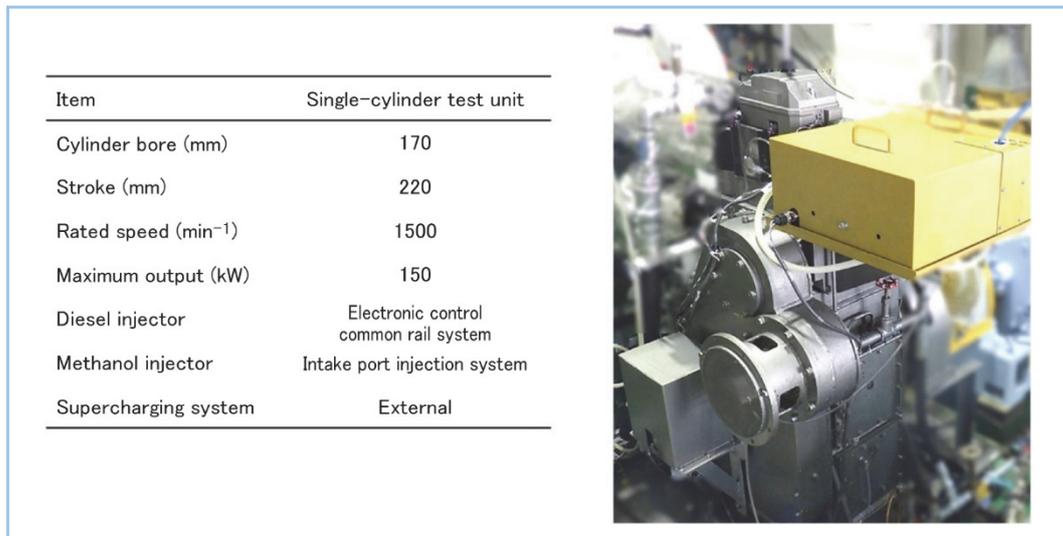


Figure 4 Single-cylinder test unit for methanol-diesel dual-fuel testing

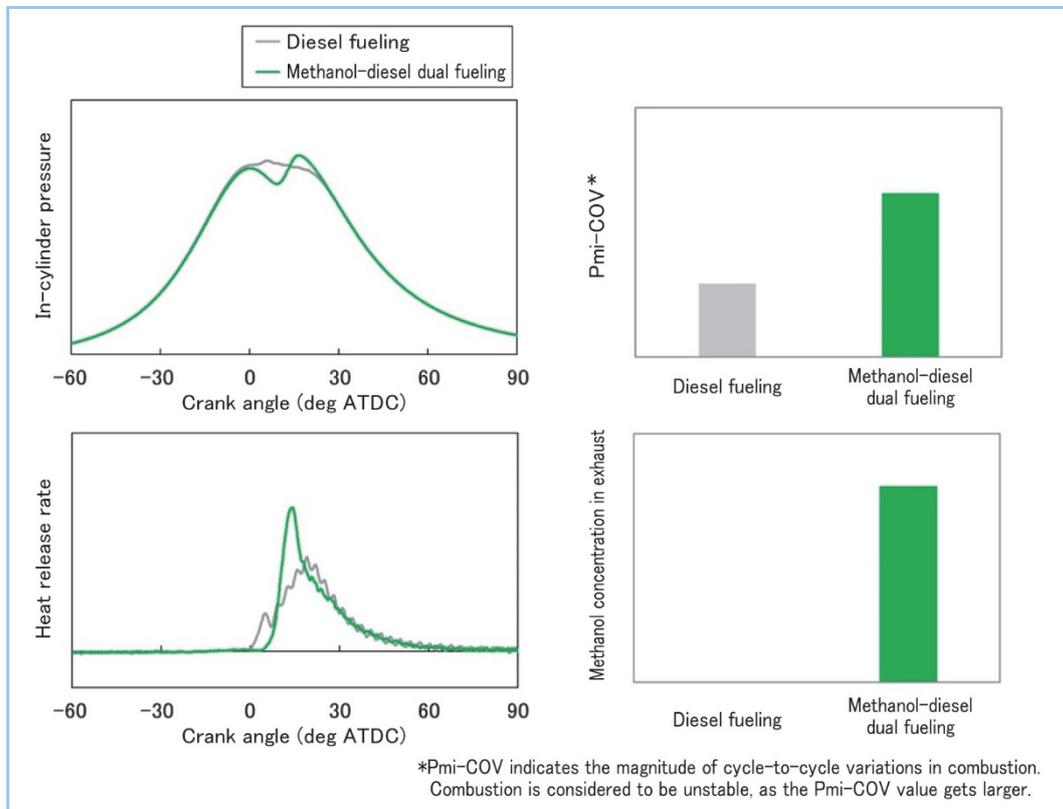


Figure 5 Test results using single-cylinder test unit: comparison between diesel fueling and methanol-diesel dual fueling

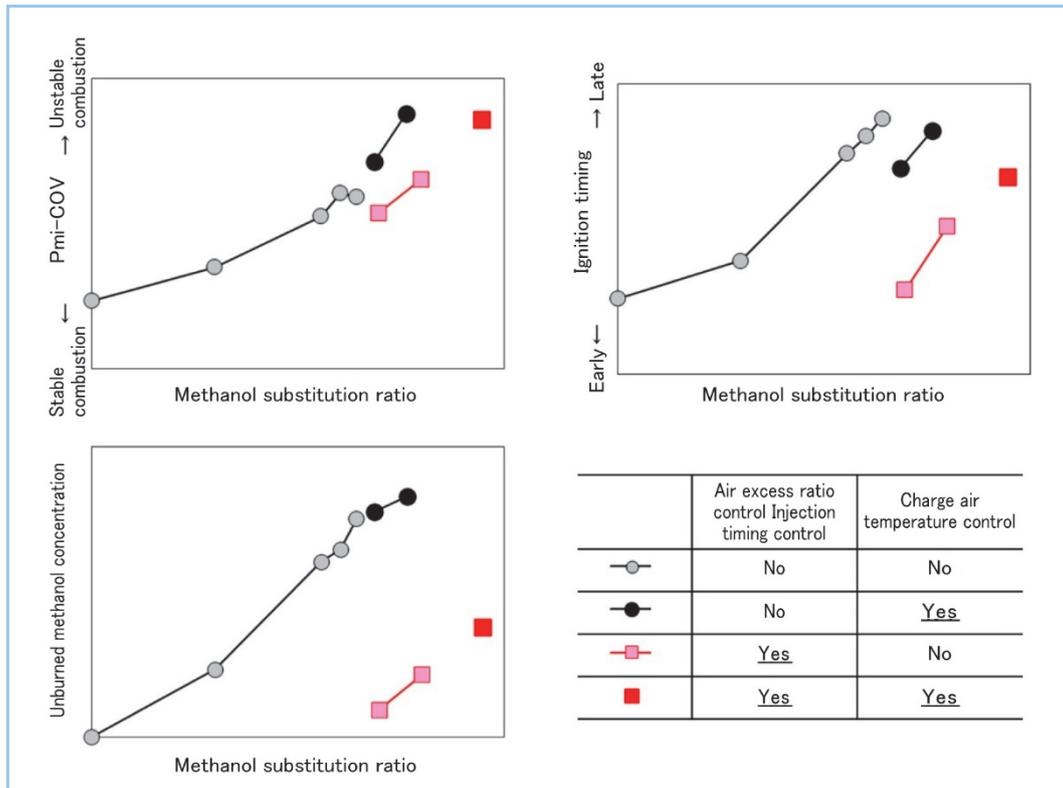


Figure 6 Combustion control for combustion stabilizing effect and higher substitution ratio

6. Conclusion

For the upcoming low-carbon/carbon-neutral society, MHI is promoting the development of a methanol-diesel dual-fuel engine with a view to introducing it as a main or auxiliary engine in marine applications. The technological issues are fluctuations in combustion and unburned methanol emissions. Currently, the optimization of methanol-air mixture formation and the development of a combustion control system are in progress using CFD analysis and a single-cylinder test unit. The developed underlying technologies will be incorporated into the SR series multi-cylinder engines for practical application. Having made the "2040 Carbon Neutrality Declaration," MHI Group works toward achieving net zero by 2040 by promoting the launch of decarbonized/low-carbon engines for power generation, marine vessels and vehicles. In this way, a contribution is made to achieving a carbon-neutral society.

References

- (1) Y. Imamori et al., Development of Hydrogen and Ammonia Engine that Contributes to Decarbonized Society, Mitsubishi Heavy Industries Technical Review, Vol.59 No.4 (2022)
- (2) T. Tanaka et al., Development of Ammonia Co-firing Engine, Mitsubishi Heavy Industries Technical Review, Vol.62 No.2 (2025)
- (3) NIPPON KAIJI KYOKAI, ClassNK Alternative Fuels Insight, https://download.classnk.or.jp/documents/ClassNKAlternativeFuelsInsight_e.pdf