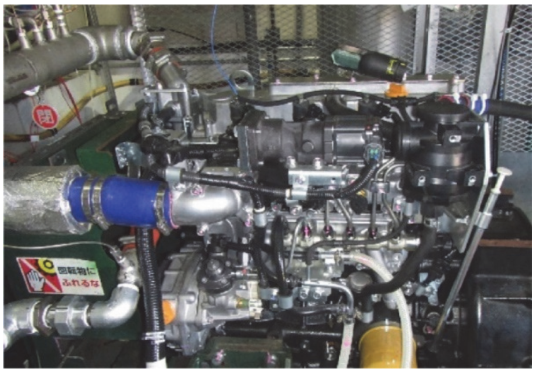
Development of Ammonia Co-firing Engine



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Toward achieving a low-carbon/carbon-neutral society, there is an increasing need for engines that can use new fuels such as hydrogen and ammonia. Ammonia is attracting attention as a marine fuel, which should be easy to handle, because of its characteristic of easily liquefying when pressurized. However, it has issues such as the presence of unburned ammonia and N_2O*, which has a greenhouse effect, in the exhaust gas when used as a marine engine fuel. To address these issues, we conducted three-dimensional combustion CFD analysis, combustion tests using a small engine, and catalyst matching for an exhaust gas after-treatment device, aiming to reduce unburned ammonia,* N_2O*, and NOx emissions. The results from the performance evaluation at the after-treatment device outlet suggested that an 89% reduction in greenhouse gas emissions, compared to diesel oil single-fuel firing of the base diesel engine, is possible.*

1. Introduction

Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. has supplied diesel and gas engines with excellent performance, reliability, and environmental characteristics for power generation, marine use, and vehicle and industrial use. Toward the achievement of a low-carbon/carbon-neutral society, we are developing engines to further improve their environmental characteristics and increase customer value with energy transition in mind [(1)].

This report presents our development status of a new engine that uses ammonia as a carbon-neutral fuel. Ammonia is attracting attention as a carbon-neutral fuel in the maritime shipping industry. Compared to hydrogen, which is also a decarbonized fuel, ammonia can easily liquefy when pressurized, making it suitable for marine fuels, which should be easy to handle. On the other hand, ammonia is characterized by its flame-retardant properties, such as its difficulty to ignite and slow combustion rate. We verified the stable combustion range and combustion characteristics of a system that co-fires flame-retardant ammonia with diesel oil through a three-dimensional combustion CFD analysis and tests using a small engine. Ammonia-fueled engines also have issues such as the presence of harmful unburned ammonia and nitrous oxide (hereinafter referred to as N_2O), which has a greenhouse effect, in their exhaust gases. We conducted catalyst-matching for an exhaust gas after-treatment device to reduce unburned ammonia, N_2O, and nitrogen oxide (hereinafter referred to as NOx) emissions.

As described above, ammonia is characterized by its excellent handling properties as a fuel, but it also has combustion issues. This report describes our initiatives and technological developments to address these issues.

2. Prediction of exhaust gas performance using CFD analysis

We studied the effect of changing the engine operating conditions (changing the ammonia co-firing ratio based on input energy) as shown in **Table 1** on the exhaust gas performance by three-dimensional combustion CFD simulations [(2)]. In this paper, the equivalent ratio Φtotal refers

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to the stoichiometric air volume required for the combustion of diesel oil and ammonia divided by the actual air volume, the equivalent ratio Φdiesel refers to the stoichiometric air volume required for the combustion of only diesel oil divided by the actual air volume, and the equivalent ratio ΦNH_3 refers to the stoichiometric air volume required for the combustion of only ammonia divided by the actual air volume. This simulation was performed using a model of a small single-cylinder of the multi-cylinder engine which was used in the experiments described below, reproducing the gas exchange in the cylinder with the opening and closing of intake and exhaust valves and the transient pressure and temperature changes in the combustion chamber with the reciprocating motion of the piston. **Table 2** shows the physical models used in this simulation. By using a reaction model that takes into account the intermediate chemical species and elementary reactions associated with diesel oil and ammonia, and their interactions, every phenomenon from ignition of diesel oil to propagation of ammonia flame was analyzed at once.

Table 1 Calculation conditions

Item	Condition at low co-firing ratio	Condition at high co-firing ratio
NH_3 co-firing ratio (%)	75	94
Φ total (-)	0.91	0.91
Φ NH_3 (-)	0.68	0.85
Φ diesel (-)	0.23	0.06

Table 2 Physical models

Item	Value
CFD code	CONVERGE
Turbulence model	LES, Smagorinsky
Spray splitting model	Modified KH-RT
Combustion model	Detailed reaction calculation
Reaction mechanism	Otomo + ERC v2

Figure 1 shows the transitions of ammonia concentration in the cylinder with respect to the crank angle and the temperature and ammonia mass distributions on the center cross-section of the combustion chamber. Up to the crank angle of 60 deg.ATDC, the unburned ammonia concentration is higher under the condition at the co-firing ratio of 94% than lower co-firing ratio case, but it becomes lower after the crank angle of 70 deg.ATDC. The contour images show that the flame reached the liner and cavity walls and a high-temperature region was formed at the crank angles of 60 deg.ATDC and 70 deg.ATDC under both conditions at the co-firing ratio of 75% and 94%. At the crank angle of 70 deg.ATDC, larger amount of unburned ammonia remains in the crevice area (enclosed by the red dashed line), and the area is smaller under the condition at the co-firing ratio of 94%. This is due to the higher combustion temperature of the ammonia flame caused by the higher co-firing ratio, resulting in higher temperature in the combustion chamber and enhanced consumption of unburned ammonia.

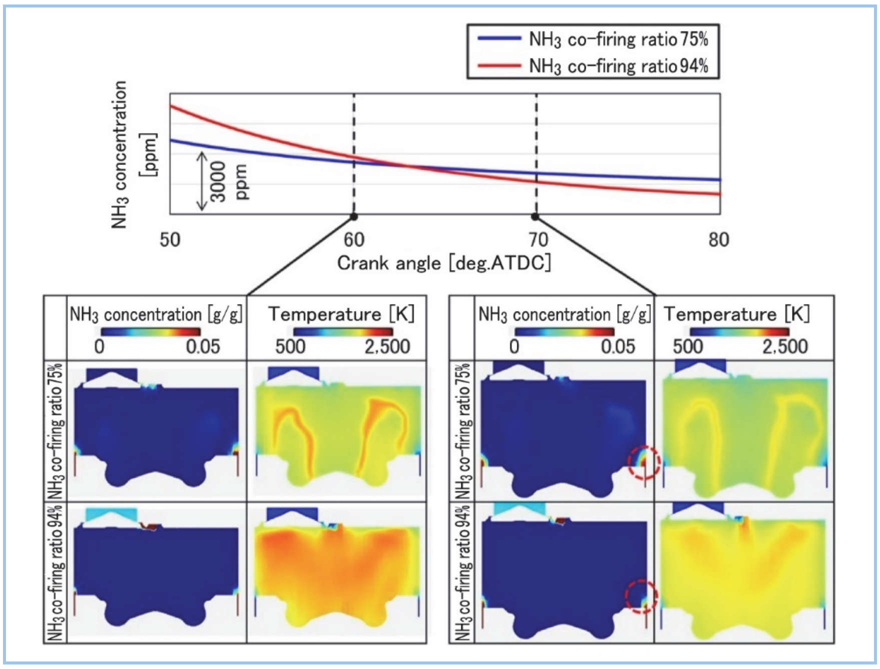


Figure 1 Transitions of NH_3 concentration in cylinder and distributions of temperature and NH_3 concentration in combustion chamber

Figure 2 shows the transition of N_2O concentration in the cylinder with respect to the crank angle and the temperature and N_2O mass distributions on the center cross-section of the combustion chamber. N_2O remained widely in the low-temperature to high-temperature region under the condition at the co-firing ratio of 75% (enclosed by the green dashed line), while it remained only in the low-temperature region under the condition at the co-firing ratio of 94% (enclosed by the blue dashed line). This is due to the increased N_2O decomposition reaction caused by the increase in combustion temperature under the higher co-firing ratio condition. These results suggest that setting the operating condition so as to increase the combustion temperature can simultaneously reduce unburned ammonia and residual N_2O.

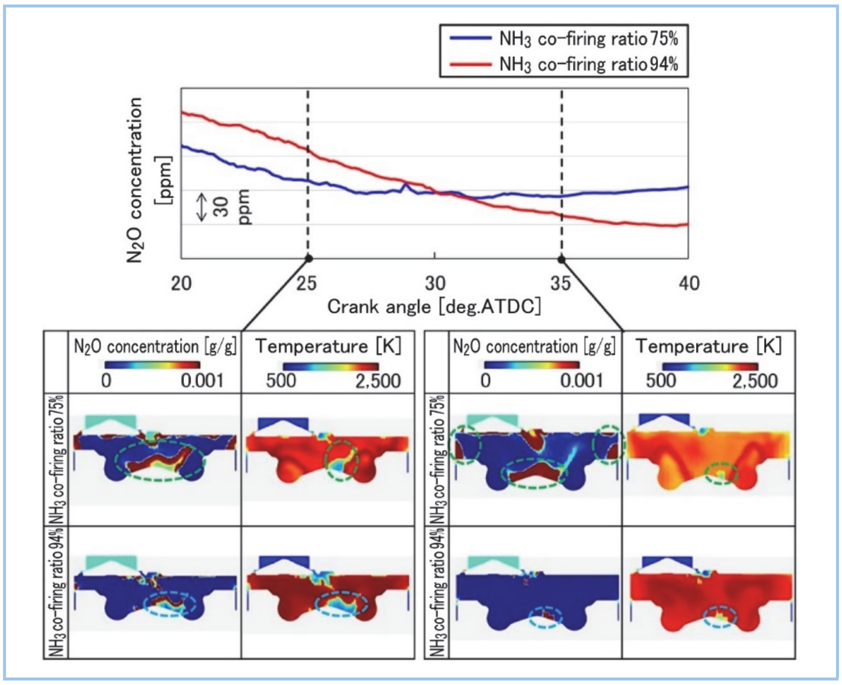


Figure 2 Transitions of N_2O concentration in cylinder and distributions of temperature and N_2O concentration in combustion chamber

3. Verification of combustion characteristics using small multi-cylinder engine

We verified the combustion characteristics in ammonia/diesel oil co-firing using a small multi-cylinder engine (3). **Figure 3** shows the system configuration, appearance, and specifications of the test engine. The system configuration was designed to supply ammonia gas to the intake piping of a diesel oil-fueled common-rail diesel engine so that the ammonia/diesel oil ratio could be adjusted as desired according to the operating conditions. By installing an intake throttle valve, the amount of engine intake air at medium and low loads could be adjusted. In addition, an exhaust gas after-treatment device using a catalyst was installed in the exhaust system, as described in detail in the next chapter.

Figure 4 shows the exhaust gas measurement results under full-load conditions. Exhaust gas component concentrations in this figure are those at the engine outlet before the catalyst. When Φtotal was increased in the order of Case 1, Case 2, and Case 3 to increase the combustion rate and promote ammonia combustion, the unburned ammonia concentration decreased and the N_2O concentration also decreased. This is probably due to a reduction in the amount of unburned ammonia, which is one of the N_2O generation factors, and an increase in N_2O consumption due to an increase in temperature in the combustion chamber caused by the increase in the equivalent ratio. In Case 3, even high ammonia co-firing ratio achieved stable combustion due to the increase in the equivalent ratio, and the co-firing ratio increased from the initial setting of 75% to 94%.

Figure 5 shows the heat release rates and their integrated values in each case when the diesel oil injection timing FIT is set to -4 deg.ATDC. As Φtotal or $ΦNH_3$ increases, the start of combustion tends to retard. This is thought to be caused by the increase of inhibiting effect on diesel oil ignition reaction by richer ammonia. In Case 3, where $ΦNH_3$ was the highest, the slope of the heat release rate slowed down around 8 deg.ATDC and then steepened again around 15 deg.ATDC. The crank angle of 8 deg.ATDC was the point at which the integrated heat release rate reached the amount of heat generated by the input diesel oil. It is considered that ammonia was burned by the flame propagation after the initial combustion of the diesel oil. **Figure 6** shows the emission rate of greenhouse gases (hereinafter referred to as GHG) at the engine outlet in Case 3. The ammonia co-firing at the co-firing ratio of 94% reduced the GHG emission rate by 82% compared to the diesel oil single-fuel firing. On the other hand, the concentration of unburned ammonia was as high as several thousand ppm, and NOx emissions tended to increase as the temperature in the combustion chamber rose. Therefore, we verified the exhaust gas characteristics when the exhaust gas after-treatment device was applied, as described in the next chapter.

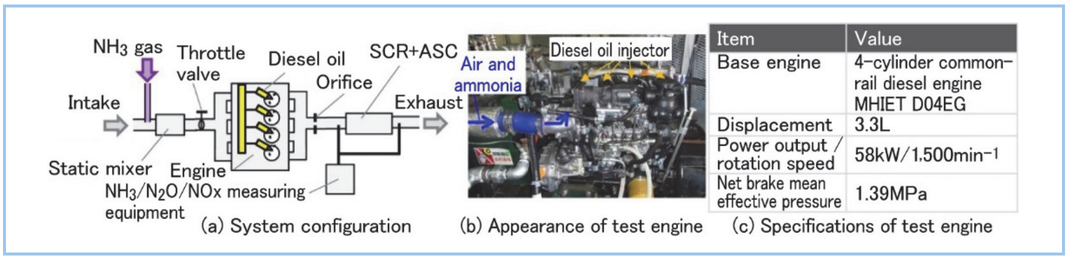


Figure 3　Summary of small multi-cylinder engine for ammonia co-firing test

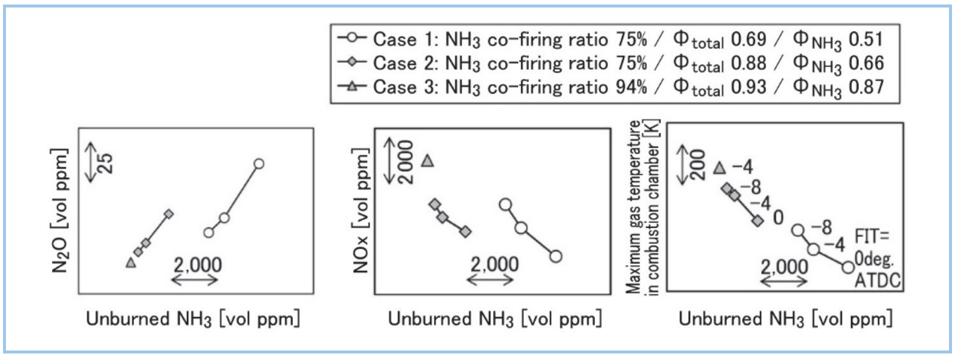


Figure 4　Test result of exhaust gas at engine outlet (full-load condition)

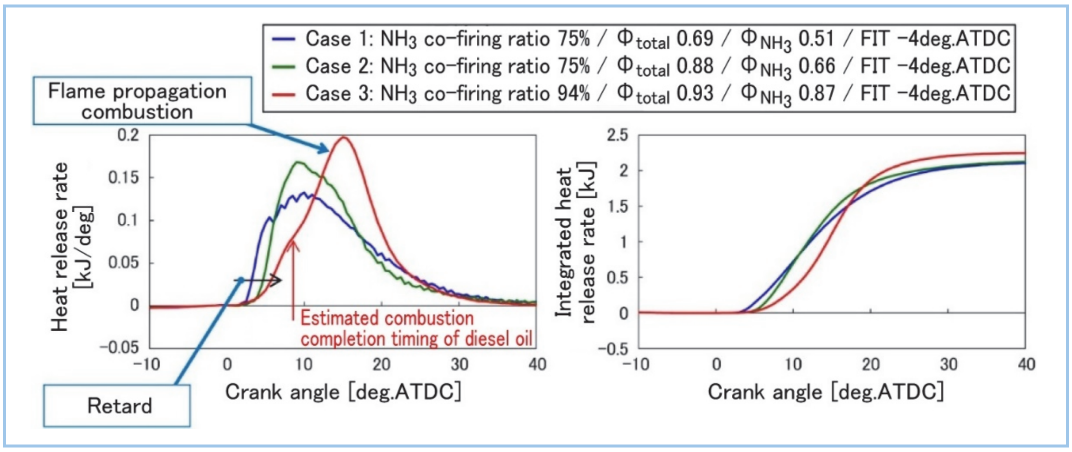


Figure 5　Heat release rate data

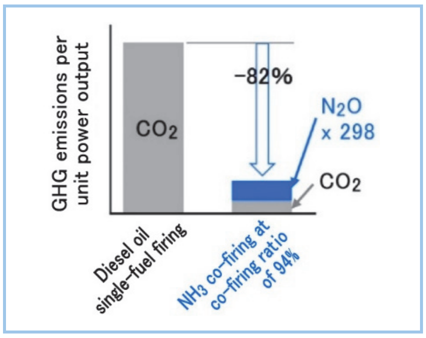


Figure 6　GHG at engine outlet

4. Verification of exhaust gas when exhaust after-treatment device is applied

The exhaust after-treatment device used in the test consisted of a selective catalytic reduction (hereinafter referred to as SCR) and an ammonia slip catalyst (hereinafter referred to as ASC). The SCR uses ammonia in the exhaust gas to remove NOx, and the ASC oxidizes excess ammonia to reduce it. This device does not have an additional supply of ammonia or urea to the exhaust system. In this test, various exhaust gas values at the exhaust after-treatment device outlet were measured while changing the engine's net brake mean effective pressure (hereinafter referred to as BMEP), i.e., load. At each BMEP, the Φtotal was increased by the intake throttle valve and the injection timing and pressure of diesel oil were optimized so that the GHG emission rate, unburned ammonia and NOx in the exhaust gas decrease and the ammonia co-firing ratio increases as much as possible.

Figure 7 shows the test results. GHG decreased as the BMEP increased, and was 89% lower compared to diesel oil single-fuel firing when the BMEP was 1.3 MPa, which corresponds to the full-load condition. Generally, there is a concern that N_2O is generated when ammonia is processed in the ASC, resulting in an increase in GHG. However, in the case of this test setup, the ratio of ammonia concentration to NOx concentration at the engine outlet was appropriate and ammonia was sufficiently consumed in the SCR, which suppressed N_2O generation in the ASC. The ammonia concentration at this time was only a few ppm, a level that is not problematic from an environmental standpoint, and the NOx concentration was low enough, confirming that the catalyst was functioning adequately. When the BMEP decreased, GHG and NOx tended to increase, but both were lower than in the case of diesel oil single-fuel firing. This is considered to be due to the decrease in exhaust gas temperature at the engine outlet for full load conditions, which reduced the catalytic function, and the increase in N_2O and NOx concentrations at the after-treatment device outlet caused by the change in the ammonia/NOx concentration ratio at the engine outlet.

The above results confirmed that this engine and after-treatment device configuration can sufficiently reduce unburned ammonia and NOx, the issue discussed in the previous chapter, when the BMEP is within the load range of 0.9 to 1.3 MPa, and can also reduce the GHG emission rate under full-load conditions by 89% compared to diesel oil single-fuel firing.

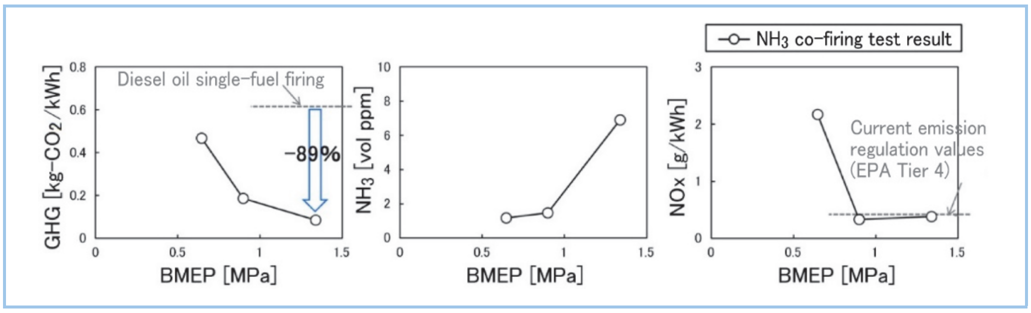


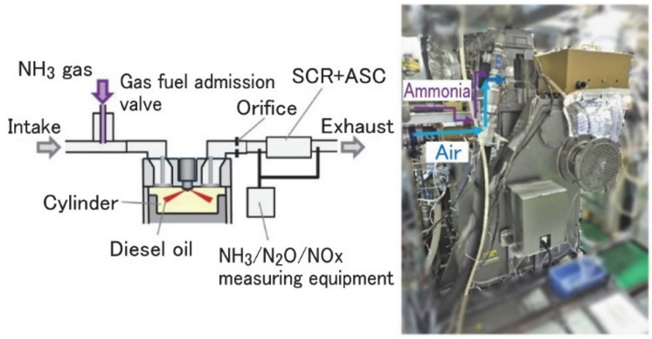
Figure 7 Results of measuring exhaust gas at after-treatment device outlet

5. Technology application to actual equipment of SR series

Based on the knowledge gained from the small multi-cylinder engine tests, we started the development of an ammonia co-firing engine for the SR series, which is currently the mainstay of our marine diesel engine line.

To understand the combustion characteristics of ammonia-diesel oil co-firing when employed in the SR series and to determine appropriate engine specifications and combustion conditions in that case, we have been conducting evaluations using a single-cylinder test engine. **Figure 8** shows the system configuration, appearance, and main specifications of the single-cylinder test engine. The system is equipped with a common-rail injection system that allows the injection amount and timing of diesel oil to be set as desired and can also perform multi-stage injection, and the air excess ratio can be changed as desired by external supercharging. In addition, the engine's intake port has an ammonia gas fuel admission valve with appropriate injection hole placement and timing to optimize the distribution of ammonia gas in the cylinder and reduce blow through during valve overlap. The exhaust after-treatment device has the same configuration as in the case of the small multi-cylinder test engine.

By understanding basic performance and exhaust gas characteristics using the single-cylinder test engine, we will confirm the feasibility of the system, including the after-treatment device in the SR series and promote the development of a full-scale multi-cylinder engine based on the confirmation results.



Item	Ammonia single-cylinder test
Cylinder bore	170mm
Stroke	220mm
Rated rotation speed	1,500min^{-1}
Number of cylinders	1
Rated power output	107kW
Net brake mean effective pressure	1.71MPa
Diesel oil injection system	Common-rail system
Ammonia injection method	Injection at intake port using gas fuel injection
Supercharging method	External supercharging
Exhaust after-treatment device	SCR+ASC

(a) System configuration (b) Appearance of test engine (c) Specifications of test engine

Figure 8 Main specifications of ammonia single-cylinder test engine

6. Conclusion

Toward the coming low-carbon/carbon-neutral society, we are promoting technological development of ammonia co-firing engines for use as marine main and auxiliary engines. We conducted verification tests of a system that includes a small multi-cylinder engine and an after-treatment device, and have demonstrated the potential for a significant GHG reduction. Based on the results of these tests, the system development is now underway for applying it to the actual parts in our SR engines. In the future, we will develop and commercialize the technology in a timely manner in response to the status of supply infrastructure development and market penetration of the fuel and the needs of society and our customers. Mitsubishi Heavy Industries group has made its 2040 Carbon Neutrality Declaration to achieve net zero carbon emissions by 2040. We, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd., will also contribute to the realization of a carbon-neutral society by developing decarbonized/low-carbon engines used for power generation, marine use, and vehicles.

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) A. Fuse et al., Effects of ammonia fraction and excess air ratio on emission characteristics of ammonia/diesel dual fueled industrial engine, the 34th Internal Combustion Engine Symposium (2023)

(3) Y. Imamori et al., Experimental and Numerical Investigations of Emission Characteristics from Diesel-Ammonia-Fueled Industry Engines, SAE Paper JSAE 20239197/SAE2023-32-0064 (2023)