CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 214

Development of an ammonia-fueled engine (28ADF) for future marine industries

Fuels - Alternative & New Fuels

Yutaka Masuda, IHI Power Systems

Yutaka Mashima, IHI Power Systems
Shunsuke Kazama, IHI Power Systems
Hiroki Naruse, IHI Power Systems
Koki Aiba, IHI
Takayuki Hirose, IHI

ABSTRACT

Ammonia fuel is an attractive option for the marine industry due to its low greenhouse gas (GHG) emissions and high energy density, compared with hydrogen and methanol. However, the application of ammonia to internal combustion engines is challenging due to its low ignitability and slow burning velocity. Therefore, a test was conducted using a rapid compression machine (RCM) to understand the combustion characteristics and ambient conditions of an ammonia/air pre-mixture ignited by pilot fuel. This RCM test was followed by a single-cylinder engine (SCE) test to verify the operating conditions and emissions of ammonia fuel in an internal combustion engine. The results of the SCE test led to modifications of a dual-fuel engine (28AHX-DF) to achieve optimal conditions for ammonia/air pre-mixture combustion.

In tests with the newly developed full cylinder engine (28ADF), stable operation with an ammonia/air pre-mixture was achieved, with a maximum fuel share ratio of up to 95%. By combining this with a catalyst, the emission of ammonia and N2O after the catalyst remained at a very low level. The GHG reduction ratio, including N2O emissions in ammonia mode, exceeded 80% compared with diesel mode, meeting the IMO GHG target for 2040. Furthermore, the IMO NOx Tier III emission regulation can be met in ammonia mode by using the catalyst.

This ammonia engine is equipped with various technologies such as ammonia-compatible materials and lubricating oil, among other things, to adapt to the use of ammonia as fuel. Furthermore, for safety issues, ammonia must be kept inside the engine and must not emit to the engine room or the atmosphere. Therefore, various measures such as crankcase vacuum control, catalyst temperature control, etc., were adapted to prevent the ammonia from emitting to the engine room or to the atmosphere.

As of February 2024, two 28ADF engines have been delivered to the shipyard for installation on a tugboat, and field testing of the ammonia-fueled engine began in mid-2024. This paper describes the performance of the ammonia-fueled engine, safety measures and the results obtained from field testing. The research and development of the ammonia-fueled full-scale engine were carried out with the aid of a grant from the Green Innovation Fund of the New Energy and Industrial Technology Development Organization (NEDO).

1 INTRODUCTION

Ammonia fuel is one of the alternative fuels for reducing greenhouse gases (GHG). The International Maritime Organization (IMO) have set the targets at the Marine Environment Protection Committee (MEPC) 80th meeting to reduce the GHG emissions by more than 20% until 2030 compared to 2008 levels, more than 70% by 2040, and 100% reduction around 2050[1].

Achieving these targets with conventional fuels is challenging, making it essential to develop engines compatible with alternative fuels. Thus, the use of zero-carbon fuels such as ammonia and hydrogen is highlighted to significantly reduce GHG emissions. The calorific value per volume is an important factor for marine fuel, as the cargo loading capacity is crucial. Ammonia has a higher calorific value per volume compared to hydrogen. Additionally, ammonia has been widely distributed globally, and its handling is well established. Therefore, the authors have focused on the development of an ammonia-fueled engine.

There are two methods for using ammonia fuel in an engine: injecting liquid ammonia at high pressure into the combustion chamber with diffusive combustion or injecting gaseous ammonia into the intake manifold with premixed combustion. In 4-stroke engines, fuel injection into the intake manifold, which is the same method as conventional gas engines, is more attractive because it requires fewer design modifications for ammonia fuel. Thus, this paper describes the development of an ammonia fuel engine with premixed combustion. The challenges of using ammonia as a fuel for internal combustion engines are its slow combustion speed and high ignition energy. Additionally, ammonia combustion emits slight amount of N_2O, which has a greenhouse effect of 265[2] times greater than CO_2 which needs to be addressed.

Using a Rapid Compression Machine (RCM), the ignition conditions and exhaust gas performance of ammonia premixture ignited by pilot fuel (Marine Diesel Oil, MDO) were clarified. The combustion condition of ammonia fuel obtained from the RCM test were then reproduced in a single-cylinder engine (SCE), to clarify the potential of stable engine operation with ammonia fuel. Furthermore, the performance with ammonia fuel in a Full-Scale engine were evaluated by applying the operation conditions obtained from the SCE test result. After the test result of the Full-Scale engine, the engine was finally commercialized and was installed to the tugboat. This paper describes the development of ammonia fuel engine and the field test from the tugboat.

2 COMBUSTION TECHNOLOGY DEVELOPMENT

2.1 Testing Apparatus and Test Condition

A Rapid Compression Machine (RCM), capable of simulating the temperature and pressure in the combustion chamber of the actual engine (Figure 1) was used to evaluate the condition required to ignite the ammonia premixture by pilot fuel (MDO). The specifications of the RCM are shown in Table 1, and the test conditions are shown in Table 2.

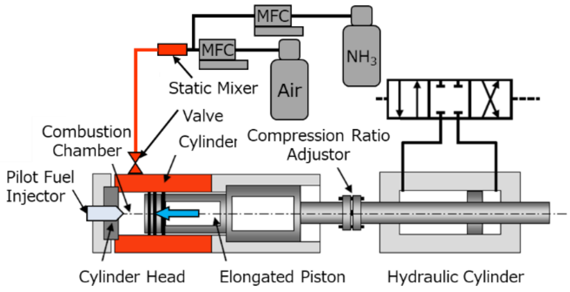

Figure 1. Schematic of Rapid Compression Machine

Table 1. Specification of RCM

Bore	150 mm
Stroke	180 mm
Swept Vol.	3.18 L
Piston Speed (Equivalent to the engine speed of)	750 min^{-1}
Maximum Cylinder Pressure	20 MPa
Hydraulic Cylinder Force	370 kN
Hydraulic Pressure	21 MPa

Table2. Test Condition

Compression Pressure	2.6～13.3 MPa
Compression Temperature	750 K
Equivalence Ratio of NH_3	0.1～1.0
Pilot Fuel Injection Timing	TDC
Pilot Fuel Injection Pressure	70 MPa
Pilot Fuel Injection Quantity	27.5 mm^3/st

2.2 Testing Procedure

The piston of the RCM is driven hydraulically, allowing it to move from the Bottom Dead Center BDC) to the Top Dead Center (TDC) at a speed equivalent to an engine speed of 750 min^{-1}. The compression temperature and compression pressure at TDC were controlled by adjusting the intake pressure, intake temperature, and compression ratio. The equivalence ratio of the ammonia premixture was adjusted by controlling the flow rate of ammonia and air using a mass flow controller. To promote the mixing of gases, the ammonia-air mixture was passed through a static mixer before supplying to the combustion chamber. The downstream pipe of the static mixer and RCM combustion chamber surface wall were heated to the same temperature as the intake air. Pilot fuel was injected at TDC to estimate the ignition and combustion characteristics of ammonia premixture under high-temperature and high-pressure conditions. The TDC temperature was adjusted to 750K and TDC pressure was varied from 2.6MPa to 13.3MPa.

2.3 Test Result

Figure 2 shows the effect of the ammonia fuel equivalence ratio on the combustion duration, which is defined as the time between 10% and 90% of the total heat release. The combustion duration is strongly influenced by the equivalence ratio of the ammonia premixture. Thus, increasing the equivalence ratio of ammonia premixture, can achieve the combustion duration comparable to that of a dual fuel engine. Additionally, the ignition of ammonia premixture can be realized with a compression temperature of 750K.

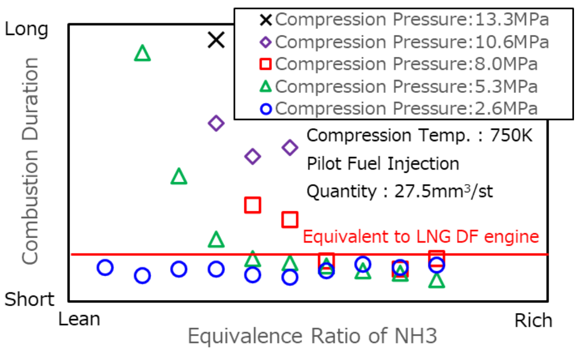

Figure 2. Combustion Duration depending on Equivalence Ratio

3 SINGLE CYLINDER ENGINE TEST

3.1 Test Engine Specification

The results from the RCM tests indicate that the combustion duration of the ammonia premixture can be controlled by the equivalence ratio of ammonia premixture. This condition was simulated in the single cylinder engine (SCE) to investigate the effects on engine stability and emission characteristics. Figure 3 shows the schematic diagram of the SCE, and Table 3 shows the specifications of the SCE. In the SCE test, gaseous ammonia fuel is continuously supplied to the intake port using a mass flow controller. This setup results in direct slip of ammonia during the valve overlap period, leading to a high amount of unburned ammonia in the exhaust. The fuel share ratio is also evaluated in the SCE test. The fuel share ratio is defined by the following equation1.

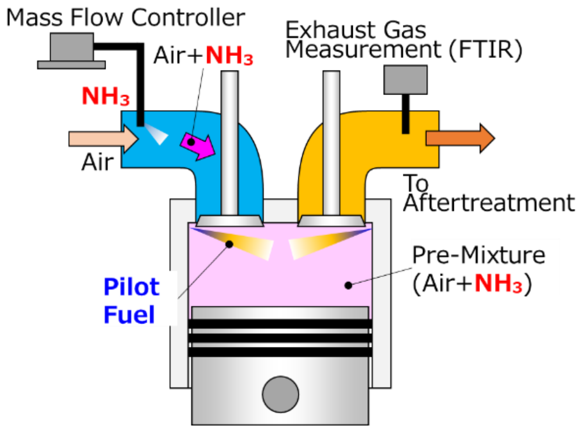

Figure 3. Schematic of SCE Test

Table3. SCE Specification

Bore	180 mm
Stroke	200 mm
Displacement	5.1 L
Rated Power	57.3 kW
Rated Speed	750 min^{-1}
Target BMEP	1.8 MPa
Number of Pilot Injector	2 (Side Injection)

$$\text{Fuel Share Ratio} = \frac{Q_{NH3}}{Q_{NH3} + Q_{pilot}} \quad (1)$$

Q_{NH3} = LHV of Ammonia fuel [kJ/cycle]

Q_{pilot} = LHV of injected Pilot fuel [kJ/cycle]

3.2 Engine Test Condition

In the SCE tests, the compression temperature at TDC and the equivalence ratio of the ammonia premixture were varied to determine the stable operating conditions of the engine and the emission performance. The stability of the engine was evaluated by the Coefficient of Variance (COV) of the Indicated Mean Effective Pressure (IMEP). The test conditions are shown in Table 4.

Table4. Test Condition of SCE

Total Equivalence Ratio (Pilot Fuel + NH_3)	0.5～1.2
Equivalence Ratio of NH_3	0.3～0.95
Intake Temperature	35～60 deg.C
Fuel Share Ratio	45～83 %
Pilot Injection Quantity	76 mm³/st
Pilot Injection Pressure	70 MPa
Pilot Injection Timing	-17 deg.CA ATDC

3.3 Engine Test Result (Effect of TDC Temperature)

Figure 4 shows the effect of TDC temperature on the COV of IMEP. The results indicate that increasing the TDC temperature reduces the COV of IMEP. Additionally, standard deviation of ignition delay becomes constant above a certain TDC temperature. Therefore, increasing the TDC temperature to a certain level is effective for achieving stable combustion.

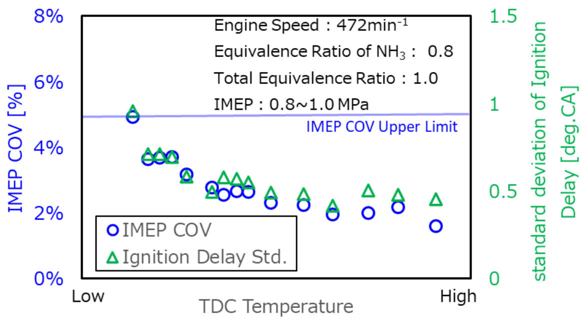

Figure 4. Combustion Stability depending on TDC Temperature

Figure 5 shows the effect of TDC temperature on exhaust gas emission. Increasing the TDC temperature reduces emissions of N2O and unburned ammonia in the exhaust gas, following the same trend as observed in previous studies [3,4]. However, a higher TDC temperature also promotes the increase of NOx. Therefore, the TDC temperature must be optimized to keep emissions of N_2O, NH_3, and NOx within permissible levels. Figure 6 shows the effect of TDC temperature on the IMEP and firing ratio (maximum cylinder pressure / compression pressure). By increasing the TDC temperature, increase in IMEP and Firing Ratio can be observed. This indicates that higher TDC temperature promotes NH_3 combustion. Therefore, higher TDC temperatures can achieve a reduction in NH_3 emissions. However, TDC temperature is limited due to component temperature and compression ratio, thus reduction of NH_3 emission by increasing TDC temperature is limited.

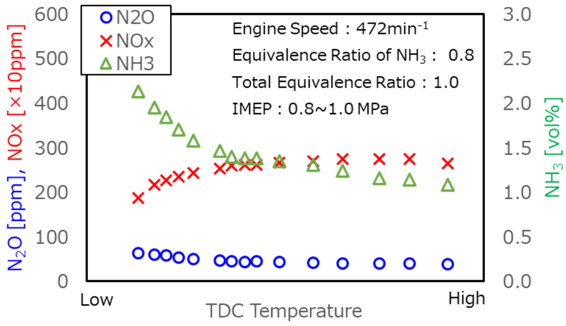

Figure 5. Exhaust Gas Emission depending on TDC Temperature

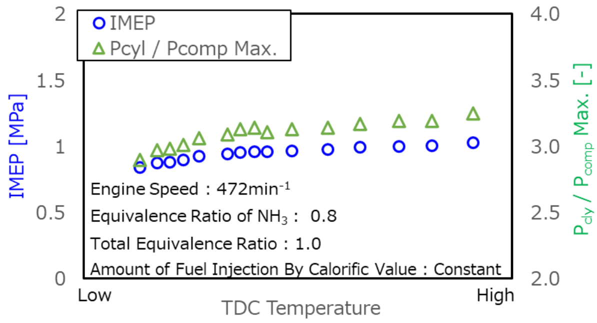

Figure 6. IMEP and Firing Ratio depending on TDC Temperature

3.4 Engine Test Result (Effect of Equivalence Ratio)

Next, the effects of equivalence ratio of the ammonia premixture on COV of IMEP, Pmax, Ignition Delay, and exhaust gas emission are evaluated. Figure 7 shows that increasing the equivalence ratio of the ammonia premixture decreases the COV of IMEP, which contributes to maintaining stable combustion. However, excessively increasing the equivalence ratio leads to a rise in the COV of Pmax. This is due to the lack of air necessary for the pilot fuel to ignite, resulting in an increased ignition delay. This phenomenon is further supported by the increase in CO emissions, as shown in Figure 8.

On the other hand, N_2O and NH_3 can be reduced by increasing equivalence ratio. NOx emission shows a peak trend depending on the equivalence ratio. These emission levels of NOx, N_2O, and NH_3 can be managed using exhaust gas aftertreatment systems.

These results indicate that controlling the equivalence ratio of ammonia premixture within a specific range can achieve both combustion stability and emission performance. The results of the SCE tests indicate a high potential for realizing ammonia premixture engines. Consequently, Full-

Scale engine tests were conducted for validation, and the exhaust gas emission performance was evaluated both before and after the exhaust gas aftertreatment (catalyst) device.

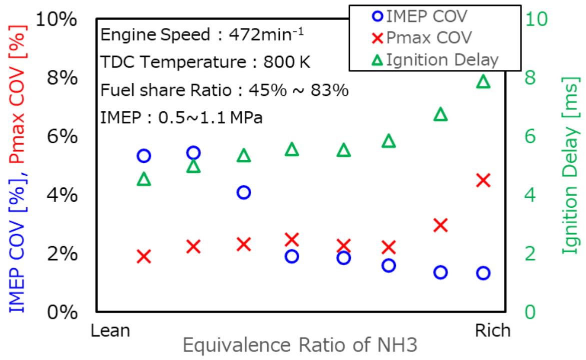

Figure 7. Combustion Stability depending on Equivalence Ratio of NH_3

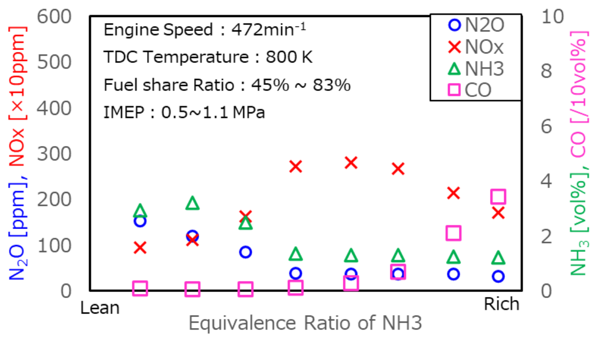

Figure 8. Exhaust Gas Emission depending on Equivalence Ratio of NH_3

4 FULL-SCALE ENGINE TEST

4.1 Specification of Full-Scale Engine

Based on the result of RCM and SCE test, a modification of 6-cylinder LNG dual fuel engine (6L28AHX-DF) was carried out to meet the requirements for ammonia fueled engine. The detailed design modifications included increasing the geometric compression ratio, optimizing the intake and exhaust systems, enlarging the fuel gas supply system, and enhancing the pilot fuel supply system. Figure 9 shows the main modifications of the Full-Scale engine, and the engine specifications are shown in Table 5. The intake and exhaust system were optimized to control the optimum air quantity for the combustion of the ammonia premixture. The diameter of the intake bypass valve, which recirculates the intake air from the air cooler outlet to the compressor inlet, was increased and a bypass valve for bypassing compressor air to the exhaust pipe was added. Additionally, a throttle valve was installed to control the equivalence ratio of ammonia premixture at low load conditions.

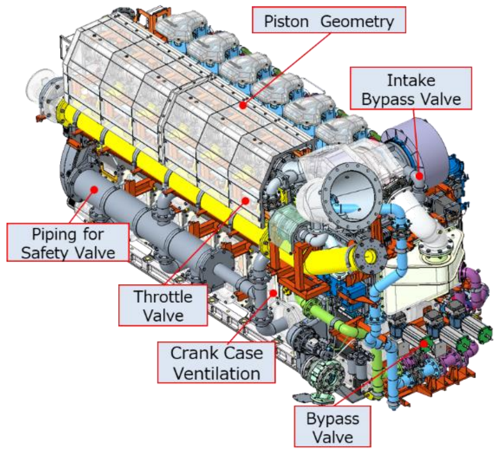

Figure 9. 3D-Image of Full-Scale Engine

Table 5. Specification of Full-Scale Engine

Engine Type	6L28ADF
Number of Cylinder	6
Bore	280mm
Stroke	390mm
Rated Power	1618kW
Rated Speed	750min^{-1}
BMEP	1.8MPa

In the Full-Scale engine, gasified ammonia fuel is injected into the intake port at an appropriate timing, which reduces ammonia slip compared to the SCE. Emission of unburned NH_3, NOx, and N_2O emission in the exhaust gas were treated by a catalyst installed in the exhaust pipe. Two Fourier transform infrared spectrometer (FTIR) were installed to measure the emission before and after the catalyst, respectively.

4.2 Engine Test Bench

The engine test bench is equipped with various auxiliary facilities such as the fuel system (NH_3, MDO), coolers for the jacket water and lubrication oil, engine starting system, exhaust piping, water brake, measuring device, alarm device, and a control device (Figure 10) [5].

The Full-Scale engine includes various proactive measures to prevent NH_3 leakage, such as double walled NH_3 fuel gas piping and a ventilation fan for the crankcase to manage NH_3 gas from the blowby. Additionally, the engine and some of the operating equipment such as fuel gas supply system (GVU) are installed within the enclosure in case an unexpected leakage. The enclosure is equipped with an intake fan and an exhaust fan, both precisely controlled to maintain the internal pressure slightly below atmospheric pressure, thereby inhibiting NH_3 leakage from in case of an emergency. The GVU is responsible for controlling the flow rate and pressure of NH_3 gas from the ammonia supply facility to the test engine and the catalyst. It also includes a function to purge the piping with N_2 gas to remove NH_3 from the fuel gas pipe before inspecting or replacing test parts. For safety, the fuel gas pipe inside the enclosure and the factory is purged daily after NH_3 operations.

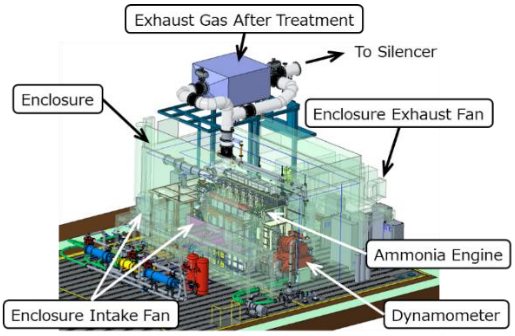

Figure.10 Schematic of Engine Test Bench

4.3 Combustion Performance

The cylinder pressure and rate of heat release (ROHR) of the LNG dual fuel engine (6L28AHX-DF which is the base engine of 6L28ADF) in LNG mode and the ROHR of diesel mode and ammonia mode in 6L28ADF were evaluated as shown on Figure11. The combustion performance, including ROHR and maximum combustion pressure in ammonia mode is equivalent to that in LNG mode by applying the ammonia premixture operating conditions obtained from the RCM and SCE test results. Additionally, it was confirmed that the fuel share ratio in ammonia mode can reach approximately 95%, which is comparable to the fuel share ratio in LNG mode.

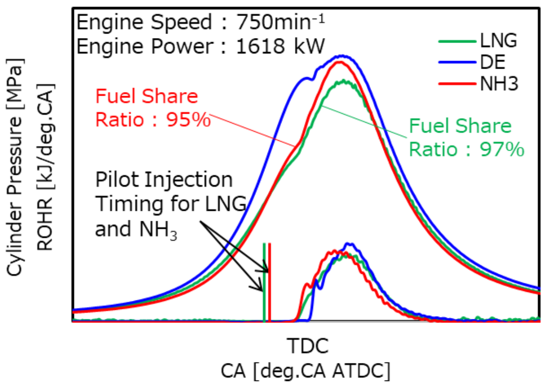

Figure 11. Cylinder Pressure and ROHR in LNG mode, Diesel Mode, and Ammonia Mode

4.4 Engine and Emission Performance

Next, Figures 12 through 16 shows the fuel share ratio and exhaust gas performance of the ammonia mode in marine E3 mode. A fuel share ratio exceeding 90% is achieved at each load in E3 mode. However, as the engine output decreases, the fuel share ratio also declines due to the requirement for a certain amount of pilot fuel to ignite the ammonia premixture.

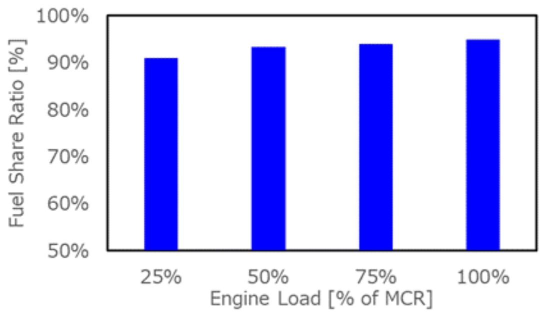

Figure 12. Fuel Share Ratio at E3 Mode

Although NH_3 emissions exceed 10,000ppm (1 vol%) at the engine outlet, as shown in Figure 13, the installation of a catalyst in the exhaust pipe reduces NH_3 emissions to approximately 0 ppm.

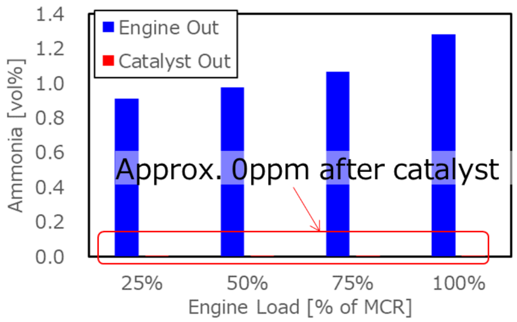

Figure 13. NH_3 Emission at E3 Mode

As shown in Figure 14, this engine complies with the IMO Tier II NOx regulation (9.6 g/kWh) in diesel mode and meets the Tier III NOx regulation (2.4 g/kWh) in ammonia mode with the use of a catalyst.

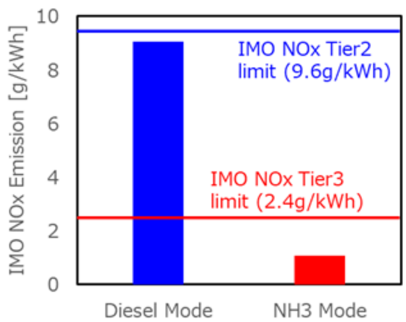

Figure 14. NOx Emission at IMO E3 Mode

As shown in Figure 15, N_2O emissions, which have a greenhouse gas effect 265 times greater than CO_2, decreased after passing through the catalyst under all operating conditions. The GHG reduction rate of the ammonia mode, considering the greenhouse effect of N_2O at the catalyst outlet, was calculated relative to the diesel mode. This calculation was performed using Equation 2, and the CO_2 density conversion factor for ammonia mode was obtained according to ISO 8178-1. The exhaust gas mass in each mode was determined by adding the fuel flow rate to the intake air flow measured from the bell mouth attached to the compressor inlet.

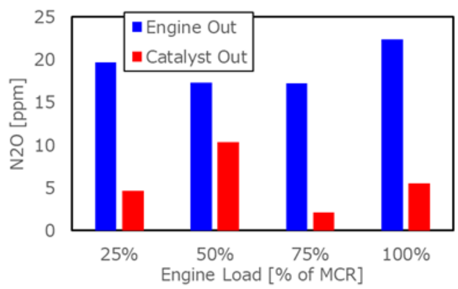

Figure 15. N_2O Emission at E3 Mode

$$\mathrm{GHG_{Reduction}} = 1 - \frac{\mathrm{U_{gasNH3}} \times (\mathrm{CO2_{gasNH3}} + 265 \times \mathrm{N2O_{gasNH3}}) \times \mathrm{q_{mewNH3}}}{\mathrm{U_{gasDE}} \times \mathrm{CO2_{gasDE}} \times \mathrm{q_{mewDE}}} \quad (2)$$

Where:

U_{gasNH3} = 0.001649 (CO_2 density conversion factor in ammonia mode)

$CO2_{gasNH3}$ = CO_2 concentration in ammonia mode (ppm)

$N2O_{gasNH3}$ = N_2O concentration in ammonia mode (ppm)

q_{mewNH3} = Exhaust gas flow in diesel mode (kg/h)

U_{gasDE} = 0.001517 (CO_2 density conversion factor in diesel mode)

$CO2_{gasDE}$ = CO_2 concentration in diesel mode (ppm)

q_{mewDE} = Exhaust gas flow in diesel mode (kg/h)

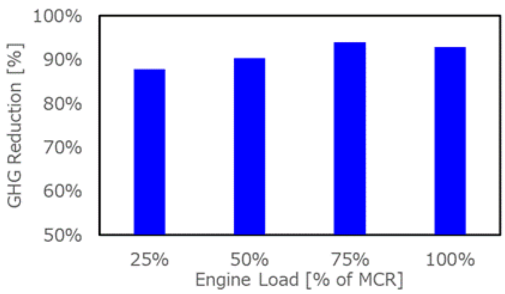

Figure 16. GHG Reduction at E3 Mode

As the result of the calculation, GHG reduction rate in the ammonia mode compared to the diesel mode in E3 mode reaches over 90% as shown on Figure 16.

4.5 Safety

Ammonia is toxic, and its odor is detectable by humans even at low concentrations. Therefore, ammonia fueled engines must be modified to prevent leakage. The fuel system supplying ammonia to the engine is designed with a double wall pipe structure to prevent leakage from pipe joints, similar to conventional LNG dual-fuel engines. Additionally, any leakage from the inner pipe can be detected using a gas detector in the annular space of the pipe. In reciprocating engines, blow-by gas that enters the crankcase can spread throughout the entire engine, posing a risk of small ammonia leaks from shaft seals and various gaps. To prevent ammonia from leaking into the engine room, a ventilation fan equipped with an oil mist separator has been installed to always maintain negative pressure inside the crankcase.

4.6 Ammonia Concentration in Each Area

The ammonia concentration in each area was measured while the engine was operating in ammonia mode, as shown in Figure 17. The ammonia concentration inside the crankcase was measured by FTIR at the downstream side of the oil mist separator.

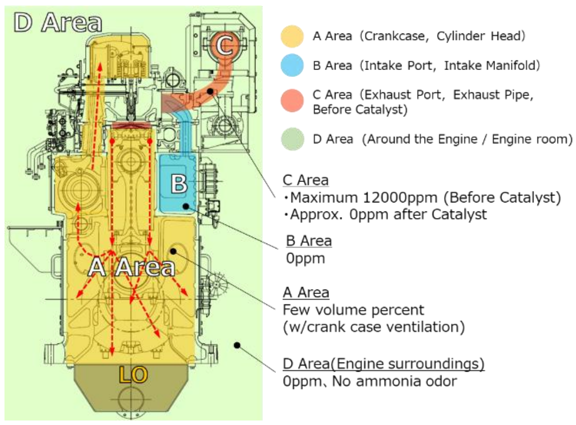

Figure 17. Ammonia Concentration and Odor around the Engine during Engine Operation

The measurement results indicated that there is ammonia blow-by inside the crankcase. However, the ammonia concentration around the engine, as measured by a gas detector, was 0 ppm, and no ammonia odor was detected. After the engine is stopped, the ammonia concentration inside the crankcase decreases to several thousand ppm. By operating the ventilation fan for the crankcase, no ammonia odor or traces of ammonia were detected around the crankcase door, even when it was opened. Therefore, it is advisable to operate the ventilation fan during maintenance as well.

4.7 Inspection of Engine Components

Ammonia is corrosive to materials such as copper, copper alloys, and various rubber materials. Therefore, components that contacts with pure ammonia gas are replaced with ammonia-compatible materials. Additionally, high-temperature ammonia gas can potentially cause material nitriding. An inspection of bearings (big end bearing, main bearing, piston pin bearing, locker arm shaft bearing, etc.) were carried out after engine testing of approximately 600 hours (300hr in Diesel Mode and 300hr in Ammonia Mode). Visual inspections revealed no corrosion or abnormal wear, as shown in Figures 18 and 19. Furthermore, energy dispersive X-ray spectroscopy (EDS) analysis showed no corrosion of copper, with no disappearance of copper or sulfide formation observed.

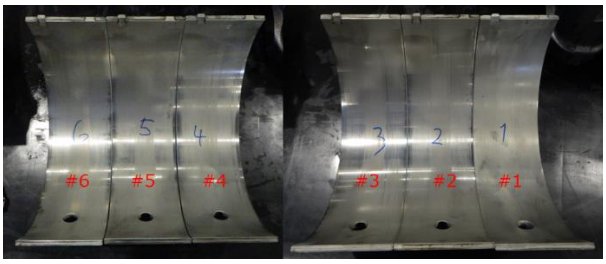

Figure 18. Inspection of Upper big end metal

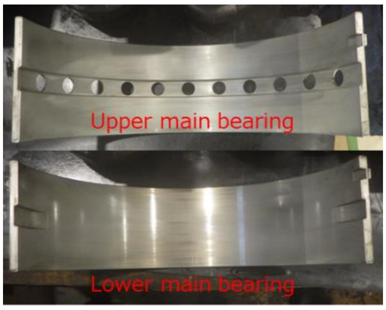

Figure 19. Inspection of main bearing metal

Nitriding of components that contacts with high temperature ammonia gas such as piston, piston ring, cylinder head, anti-polish ring, exhaust gas manifold, etc. were examined. Inspection results from Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Spectroscopy (EDS) showed no evidence of nitriding on these components, as shown in Figure 20. In conclusion, no signs of corrosion damage or nitriding were observed in the components after approximately 600 hours of engine testing. Further investigation will be conducted during field tests.

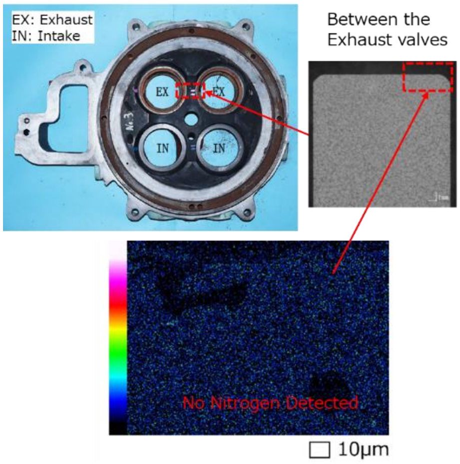

Figure 20. Nitriding inspection of Cylinder Head

5 FIELD TEST OF AMMONIA FUELED ENGINE

In January 2024, two ammonia-fueled engines (Figure 21) were delivered to the shipyard and installed in a tugboat. The modification of the previous LNG fueled tugboat, SAKIGAKE, was undertaken to accommodate the ammonia-fueled engines and the ammonia fuel system. This tugboat was delivered to the shipowner on August 23, 2024, marking it as the world's first commercial ammonia-fueled vessel, as shown in Figure 22.

Figure 21. Picture of 28ADF

As of November 21, 2024, the engine has operated for approximately 460hrs, with 58hrs using ammonia fuel. No major abnormalities have been observed during operation. Future investigations in the future will examine the components for corrosion damage, nitriding, and other effects from ammonia exposure. Given the importance of transient characteristics for tugboats, a comparison of transient operations between diesel mode and ammonia mode was conducted under propeller curve conditions. The results, shown in Figure 23, shows that the same acceleration speed was achieved in both ammonia and diesel mode.

Figure 22. Picture of Tug Boat "SAKIGAKE"

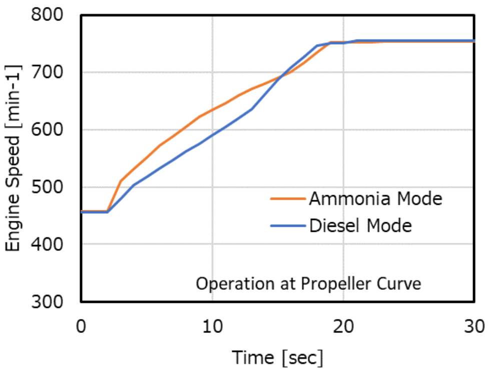

Figure 23. Acceleration Performance in Diesel Mode and Ammonia Mode

6 CONCLUSION

The authors have developed ammonia fueled medium speed 4-stroke engine that contributes to reducing GHG emission from ships. Using RCM, the ignition conditions and combustion characteristics of an ammonia premixture using pilot fuel were clarified. By simulating the condition obtained from RCM test to SCE, the feasibility of operating the engine using ammonia fuel was confirmed. Based on these results, a Full-Scale engine was modified and demonstrated its performance and effect of ammonia on the components were evaluated. The engine was ultimately delivered to a tugboat, where its performance was successfully demonstrated. Through the development process, the following results were obtained.

1) Stable operation of the ammonia-fueled Full-Scale engine is achieved by optimizing the conditions of ammonia premixture (compression end temperature and pressure, equivalence ratio, etc.) and Pilot Injection condition (injection timing, quantity, etc.).

2) A GHG reduction rate of over 85% was achieved in ammonia mode compared to diesel mode.

3) Unburned ammonia and N_2O in the exhaust gas were kept at very low level at each load in marine E3 mode by using a catalyst.

4) The Full-Scale engine test confirmed that the ammonia engine complies with IMO NOx Tier III regulations in ammonia mode.

5) No ammonia odor or emissions were detected around the engine by maintaining constant negative pressure inside the crankcase, allowing for safe operation with ammonia fuel.

6) No effect of ammonia on the engine components such as bearings and cylinder head, etc. were found within the shop test operation hours. Further investigation will be carried out on the field test.

7) Ammonia engine was developed based on the RCM and SCE tests and was realized through a Full-Scale engine test. Also, the demonstration of field operation was conducted by installing the Full-Scale engine on the Tugboat.

7 ACKNOWLEDGEMENTS

The research and development of the ammonia-fueled Full-Scale engine were carried out with the aid of a grant from the Green Innovation Fund of the New Energy and Industrial Technology Development Organization (NEDO). The authors would like to express their deep gratitude for this opportunity.

8 REFERENCES

[1] IMO MEPC80 (2023) ANNEX1. https://wwwcdn.imo.org/localresources/en/MediaCentre/PressBriefings/Documents/Clean%20version%20of%20Annex%201.pdf

[2] IPCC Fifth Assessment Report 2013, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf

[3] Niki, Y., Nitta,Y., Ichikawa, Y., Sekiguchi, H. and Hirata, K. 2018. Emission and combustion characteristics of diesel engine fumigated with ammonia, ASME 2018 Internal Combustion Engine Division Fall Technical Conference

[4] Tamaoki, K., Kanayama, K., Tezuka, T. and Nakamura, H. 2024, Self-induced radical sensitization in ammonia oxidation at intermediate temperatures and elevated pressures, Combustion and Flame, Vol.269, 113658

[5] Tagai, T. 2023. Development of Ammonia-fueled 4-Stroke Marine Engines, Journal of the Japan Institute of Marine Engineering, Vol.58, 679-684