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Combustion development of an ammonia diesel dual-fuel medium-speed marine engine

Emission Reduction Technologies - Engine Measures & Combustion Development

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ABSTRACT

Ammonia is a carbon-free fuel. Using ammonia as fuel in marine engines is considered to be one of the effective ways for the marine industry to achieve carbon reduction targets. Moreover, ammonia, as marine fuel is expected to be the cheapest green fuel, and the demand for ammonia in shipping is expected to be high.

However, ammonia fuel itself has negative combustion characteristic, e.g., its high ignition temperature, extremely high ignition energy, very slow flame speed, and narrow flammability limit, etc. The combustion organization of ammonia-fueled engines may have new challenges. The current studies have demonstrated that ammonia can be used as an alternative to fossil fuels for compression-ignition engines, but most results are based on article engines[LK1] , few combustion research has been published about large bore size marine ammonia engines.

This paper presents the investigation of the ammonia combustion characteristics based on a large-bore four-stroke single cylinder engine with port ammonia admission. The combustion programs investigated include different ammonia substitution rates, intake conditions, fuel injection parameters, etc. And the combustion and emission test results, including the cylinder pressure, heat release, the thermal efficiency, and NH_3/NO_x/N_2O/CO_2 emission, etc. are presented. The results show that the highest brake mean effective pressure is 2.2 MPa and the highest ammonia energy substitution rate is up to 85%.

1 INTRODUCTION

In July 2023, the IMO adopted a new strategy for reducing greenhouse gas emissions from ships, significantly advancing the goal of achieving zero carbon emissions from the original 2100 to 2050 [1], making it increasingly urgent to achieve zero carbonization of ship engines.

Figure 1 IMO's GHG strategy

Ammonia is a zero carbon fuel that does not produce CO_2 during combustion. The products of complete combustion are only nitrogen and water. Ammonia can liquefy at -33 ℃ or 9 bar at room temperature, making it easy to store and transport. It is considered an ideal alternative fuel for achieving zero carbon emissions in engines.

In September 2023, the IEA predicted that the share of ammonia in final energy consumption would reach 44% by 2050 [2].

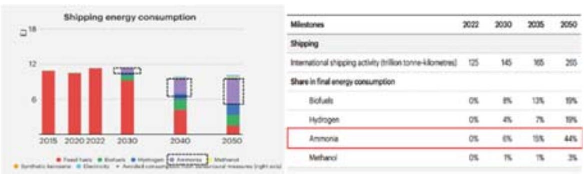


Figure 2

On June 13, 2024, the ABS just released a new version of "Beyond the Horizon, Carbon Neutral Fuel Pathways and Transformational Technologies." It is predicted that by 2050, the market share of traditional fossil fuels will decrease to 15%; The usage share of ammonia is expected to increase to 33% [3]. In 2023, DNV released the 7th edition of the Maritime Forecast to 2050, which predicts that by 2050, the total share of low-carbon and zero carbon fuels will be 84%. Among them, the usage share of ammonia is about 36% [4]. LR predicts in its report 'The Future of Offshore Fuels' that by 2050, blue ammonia and green ammonia will jointly occupy 20-60% of the shipping fuel market, averaging 46% across all scenarios, and predicted by 2050, the most promising and widely adopted alternative fuel for shipping will be green ammonia [5]. Marine ammonia fuel engines have broad development prospects.

However, ammonia fuel has the characteristics of high ignition temperature, extremely high ignition energy, slow flame propagation speed, and narrow flammability limit, making it difficult to combustion. If it is a compression ignition pure ammonia engine, the compression ratio needs to reach 35 or more to achieve stable ignition [6], so a strong ignition source is generally needed. The ammonia diesel dual fuel engine can be based on existing diesel engines, with minor modifications to the fuel supply system, using the original direct injection diesel to ignite ammonia fuel and achieve stable combustion. It is considered one of the important routes for future ammonia fuel engines. The main technical paths for ammonia diesel dual fuel engines are LPDF in the ammonia intake duct and HPDF in the liquid ammonia cylinder [7]. The LPDF path requires minimal modifications to the engine and has relatively low requirements for the injection system, making it a widely researched technology path for ammonia diesel engines.

Reiter et al.[8][9] investigated the influence of ammonia substitution ratio on the combustion and emissions characteristics of engine using a dual-fuel approach with ammonia and diesel fuel. Niki et al. [10][11] and Yousefi et al.[12][13] studied the effect of different diesel injection parameters to thermal efficiency and emissions from ammonia-assisted diesel engine..

Due to the low ignitability and combustion speed, the application of NH_3 on diesel engine needs to be ignited and properly organized, especially for marine diesel engines. Since the bore is particularly large, in the case of high ammonia AER, diesel penetration may be insufficient, so that ammonia at the far end of the combustion chamber may not be ignited, resulting in high emission of unburned ammonia.

This paper details the combustion development of CS27DF-A, a new member of SMDERI marine engine family.

2 CS27DF-A ENGINE FEATURE

SMDERI is a qualified organization integrating research and development, design and manufacturing in the field of high-power engine. SMDERI has been developing various types of high and medium speed diesel engines for many years. In the end of 2023, SMDERI had successfully developed CS27 diesel engine delivered to the customer. CS27 series diesel engines have a power range of 2~3MW, and the emissions can meet IMO Tier II. With SCR, they can meet IMO Tier III. In order to achieve low fuel consumption, CS27 diesel engine adopts variable valve mechanism, adjustable supercharging system and high pressure common rail system. Through multi-objective and multi-parameter performance optimization, the minimum fuel consumption of 180g/kWh is achieved, and the performance under low load was optimized.

As a new-generation low-carbon emission marine engines, CS27DF-A was developed independently by SMDERI basing on CS27, to meet the goal of carbon neutrality. The layout of 6CS27DF-A ammonia dual fuel engine as follows Figure 3.

Figure 3 CS27DF-A ammonia dual fuel engine layout

CS27DF-A can be use for propulsion for container, bulker, chemical products ships, offshore vessels, workboat & tugs and other types of river and coastal vessels; Auxiliary gensets for various ocean ships. Based on the market demand, CS27DF-A is available in two versions, one with a power per cylinder of 310kW at 750r/min and the other with power per cylinder of 300kW at 720r/min, covering a power range of 1-3MW, with a maximum energy rate of ammonia up to 85%. The basic technical engine data of the CS27DF-A are shown in Table 1.

Table 1 Technical parameters of CS27DF-A

Item	Value
Bore (mm)	270
Piston stroke (mm)	390
Number of cylinders (-)	6/8/9
Engine speed (r/min)	720/750
Rated power (kW)	1800~2790
BMEP (MPa)	2.2
Max. ammonia energy rate (%)	85
Ammonia supply	Port injection
Diesel supply	Common rail and direct injection

CS27DF-A has been certified by the CCS in December, 2024. The main features are as follows:

- Maximum reduction of carbon emission reaches 82% using green ammonia
- Diesel and ammonia dual fuel modes with electric-controlled injection technology flexible switch between two fuels
- Meet the IMO Tier II and IMO Tier III (SCR equipped) emission regulation Intrinsically safe design

The main modified systems of CS27DF-A include diesel injection system, ammonia supply system, and control system.

The diesel injection system of CS27DF-A adopts the high-pressure common rail system of CS27 diesel engine, with a maximum rail pressure of 1600bar. However, in order to meet the demand for the use of the CS27DF-A dual fuel engine, it is necessary to ensure full load operation in diesel mode, as well as the stability of diesel small fuel injection under low load with high AER in ammonia mode. Therefore, stability design optimization was carried out for diesel injectors under wide operating conditions. Figure 4 shows the diesel injection system.

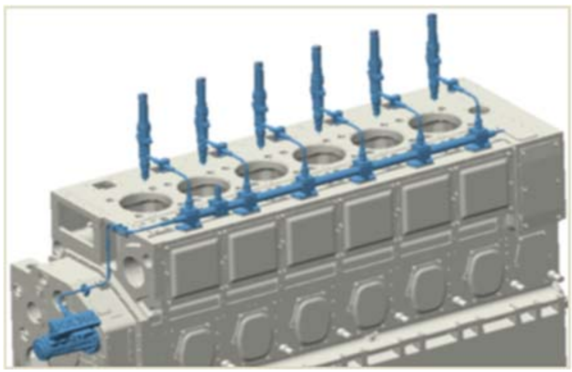


Figure 4 The diesel injection system

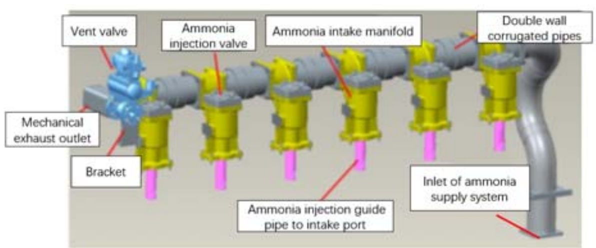


Figure 5 Double wall ammonia injection system

CS27DF-A ammonia injection method is multi-point intake port injection, as shown in Figure 5. The ammonia injection system is double wall system, which consists of ammonia intake manifold, corrugated pipes, injection valves, a vent valve, and sensors. The high flow ammonia injection valve suitable for marine engine are developed by SMDERI.

Compared to CS27, the main changes to the control system of CS27DF-A are the addition of an ammonia injection control unit, as well as the addition of dual fuel mode switching function, control strategy for switching to diesel mode in the security control strategy, and purge control strategy.

3 COMBUSTION DEVELOPMENT

3.1 Combustion investigations on ORCM

For fundamental research and understanding of NH_3-combustion, investigations of the effects of NH_3 energy ratio, equivalence ratio, diesel injection pressure on the ignition and flame propagation of NH_3/diesel dual fuels were carried out on a ORCM . The detailed description of the ORCM and results are given in [14][15].

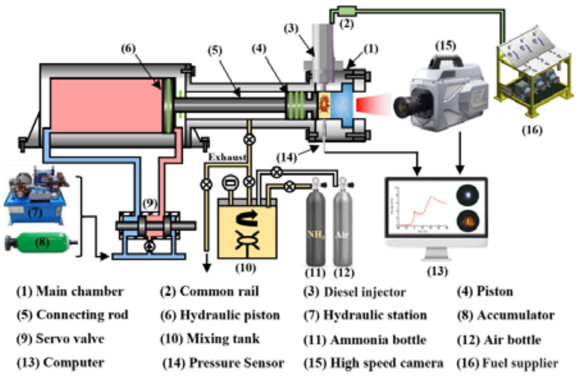


Figure 6 Experimental schematic of ORCM [14]

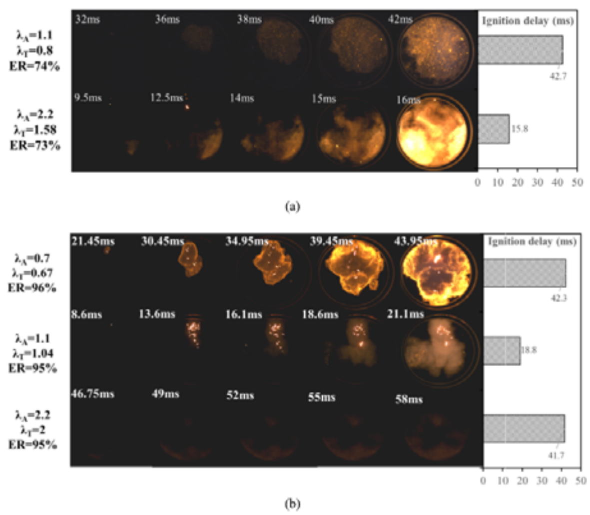


Figure 7 Ignition and flame propagation of NH_3/diesel under different AER and λ_T. [14]

The main results on ORCM are that the spray and distribution of diesel and the equivalence ratio play the key role in the NH_3/diesel dual fuels combustion, and Low pressure and temperature will cause ammonia cannot combust. These findings were transferred to the combustion parameters that are tested on SCE.

3.2 Combustion development on SCE

3.2.1 Experimental setup

Detailed optimization of the combustion system of CS27DF-A was performed on a NH_3/diesel dual-fuel SCE, in which ammonia gas is premixed with air through the injection valve arranged on the intake port. Diesel is directly injected into the cylinder through the high-pressure common-rail fuel injection system to ignite the ammonia-air mixture. The main technical parameters of the engine are shown in Table 1, and the schematic of the experimental setup is shown in Figure 8.

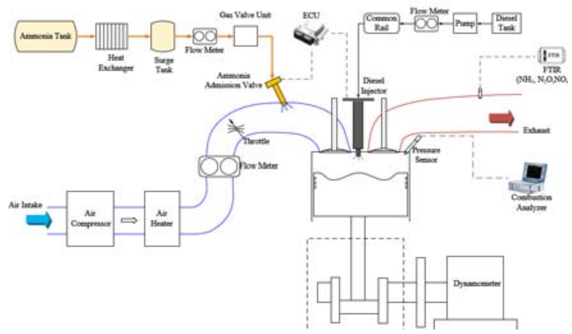


Figure 8 Schematic of a NH_3/diesel dual-fuel single cylinder engine

Figure 9 The ammonia supply system of the NH_3/diesel dual-fuel SCE

The ammonia injection valve is arranged on the engine cylinder head, and gaseous ammonia is injected into the intake port through the ammonia injection valve. Ammonia injection pressure, injection pulse width and injection timing can be controlled by ECU. The ammonia injection pressure is adjustable from 1 to 6 bar. The in-cylinder diesel direct injection system is a high-pressure common-rail fuel system. Diesel injection pressure, injection timing, injection pulse width and other parameters are controlled by ECU. The maximum diesel injection pressure is 1600bar.

The intake and exhaust system are single-cylinder simulated booster system, including intake air compressor, intake heating module, intake regulating valve, exhaust regulating valve, etc., which can simulate different intake pressure, intake temperature, exhaust pressure and other inlet and outlet cylinder gas conditions. The intake and exhaust conditions ensures that the operating values measured on the single cylinder engine are very good approximations to the values measured later on the multi cylinder engine.

The cylinder pressure is measured by Kistler 6045B pressure sensor located on the cylinder head, and the cylinder pressure signal is connected to combustion analyzer to obtain combustion characteristic parameters. Emission parameters such as NH_3, N_2O, NOx, and CO_2 were obtained by FTIR.

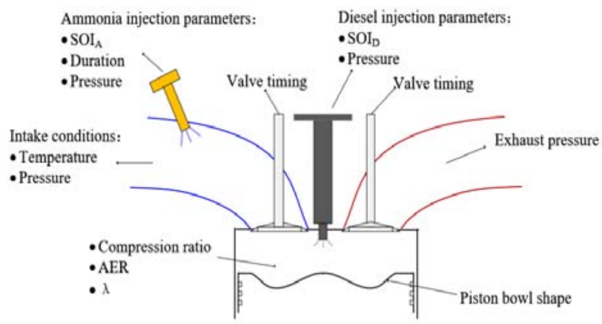


Figure 10 Combustion development parameters

During combustion development, parameters which influence the ammonia combustion within the cylinder were optimized (see Figure 10).

3.2.2 Optimization of AER

AER (Equation 1) plays a key part in the combustion development of the CS27DF-A as it has decisive impact of the engine combustion and emission performance.

$$AER = \frac{B_{NH_3} \times LHV_{NH_3}}{B_{Diesel} \times LHV_{Diesel} + B_{NH_3} \times LHV_{NH_3}} \times 100\% \quad (1)$$

Where B_{NH3} and B_{Diesel} are respectively the mass flow of the ammonia and diesel in kg/h, LHV_{NH3} and LHV_{Diesel} are respectively low heat value of ammonia and diesel in kJ/kg.

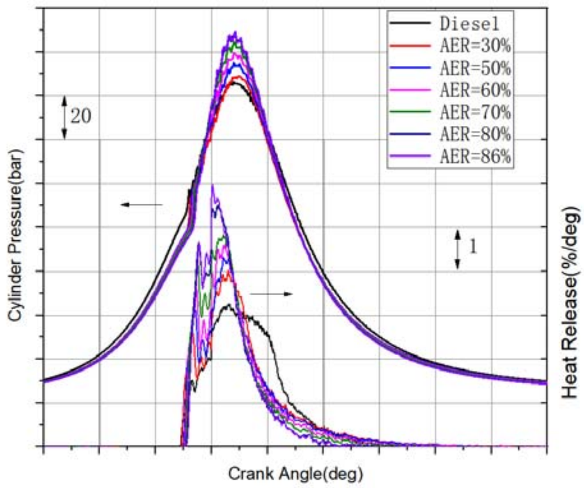


Figure 11 Comparison of cylinder pressure curves and heat release curves for different AERs at 75% load

Experimental studies were conducted on different AERs under different loads. Figure 11shows the pressure and heat release curves of different AERs at 75% load.

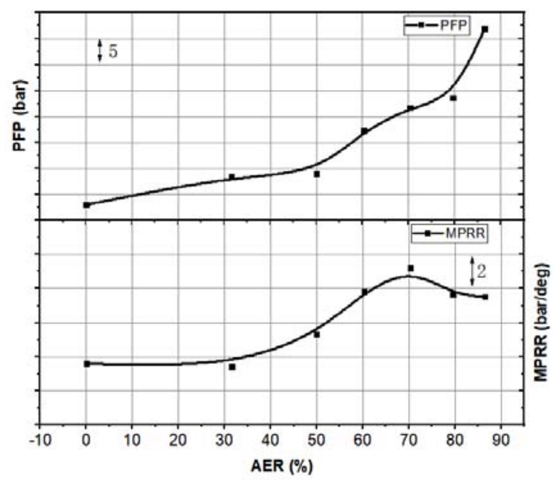


Figure 12 Comparison of PFP and MPRR for different AERs at 75% load

The combustion phasing is shown in Figure 13. Affected by the characteristics of ammonia fuel, the ignition delay of ammonia mode is generally longer than that of diesel mode, and it increases linearly with the increase of AER. At ammonia mode, diesel fuel burns at multiple points near the TDC, igniting the premixed ammonia, resulting concentrated combustion, leading to an earlier CA50 & CA90 and a shorter combustion duration, especially when the AER exceeds 50%.

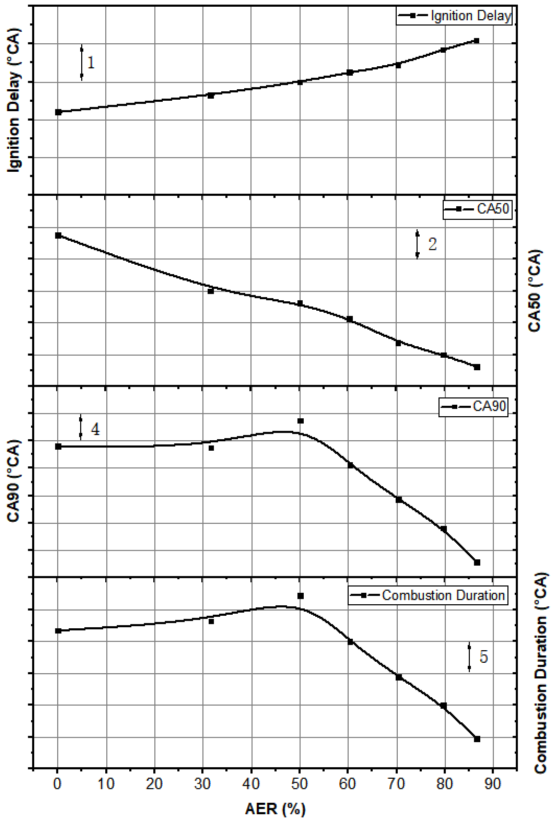


Figure 13 Comparison of combustion phasing for different AERs at 75% load

Figure 14 compares the BTE and exhaust temperature for different AERs. Due to the concentrated combustion of ammonia mode, the exhaust temperature is lower than that of diesel mode, which may lead to lower turbocharge air pressure for multi cylinder engine. Although research has shown that the flame propagation speed of ammonia is very slow and may affect combustion efficiency, SCE tests have verified that because of the premixed ammonia concentrated combustion as mentioned earlier, heat release occurs at the TDC, the ITE of ammonia mode not being lower even higher than that of diesel mode.

AER has a significant impact on engine emissions, as shown in Figure 15. With the increase of AER, NO_X first decreases and then increases, and at high AER, NO_X emission is much higher than diesel mode. NH_3 emission increases with the increase of AER, but it stabilizes when AER is higher than 70%.

N_2O is a special and noteworthy emission for ammonia engine, since the global warming potential of N_2O is about 265 times that of CO_2 over a 100-year time horizon [16]. The test shows that N_2O emission decreases inversely at high AER.

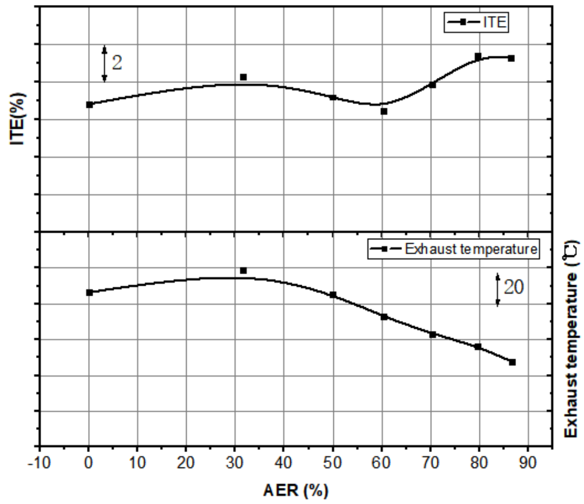


Figure 14 Comparison of ITE and exhaust temperature for different AERs at 75% load

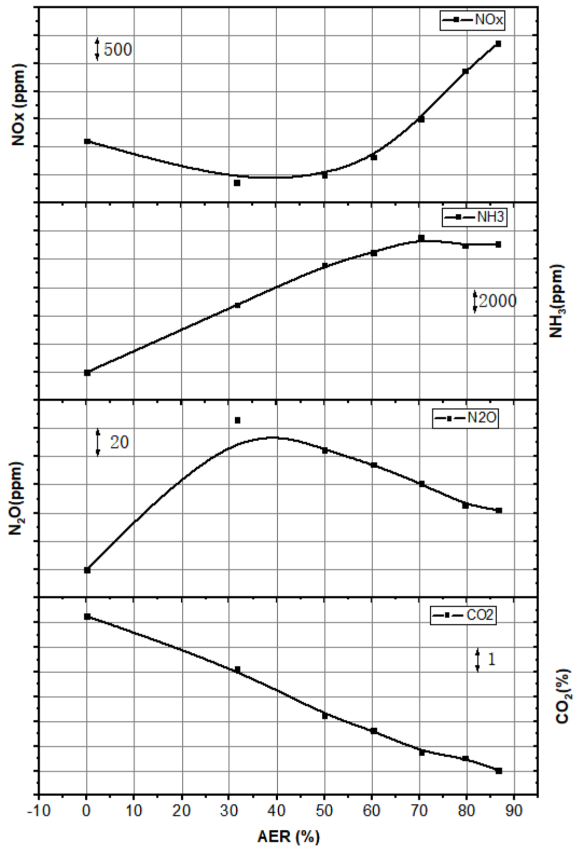


Figure 15 Comparison of emissions for different AERs at 75% load

From the point of view of reducing CO_2 emissions, it is hoped that the higher the AER, the better. But for CS27DF-A, it needs to take into account the combustion stability, mechanical load, thermal load, different emissions and BTE to determine the AER for different loads.

3.2.3 Optimization of λ

The λ is defined as Equation 2. λ is another key parameter for ammonia combustion and emission.

$$\lambda = \frac{B_{air}}{B_{Diesel} \times AFR_{Diesel} + B_{NH_3} \times AFR_{NH_3}} \quad (2)$$

Where B_{air}, B_{NH3} and B_{Diesel} are respectively the mass flow rate of the air, ammonia and diesel in kg/h, AFR_{NH3} and AFR_{Diesel} are respectively stoichiometric air/fuel ratio of ammonia and diesel.

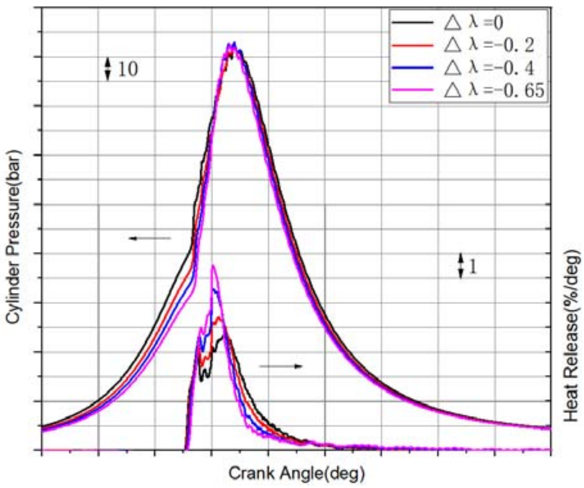


Figure 16 Effect of λ on pressure and heat release at 75% load with 70% AER

The λ affects the peak heat release. The smaller the λ, the higher the peak heat release. But the impact of λ on PFP is not significant. (Figure 16).

The effects of λ on emissions are shown in Figure 17. As the λ decreases, the mixture becomes richer, which is more conducive to ammonia combustion. Unburned NH_3 decreases, and due to the richer mixture, the combustion temperature in the cylinder increases, resulting in reduced N_2O emissions. At the same time, a richer mixture and higher temperature are also beneficial for diesel combustion, leading to an increasing trend in CO_2.

Experiments have shown that there are different optimal λ values for different loads and AER in ammonia mode, and the λ demand in ammonia mode is lower than that in diesel mode. Therefore, the CS27DF-A multi cylinder engine adopts a adjustable boost system with exhaust bypass valve to improve its performance.

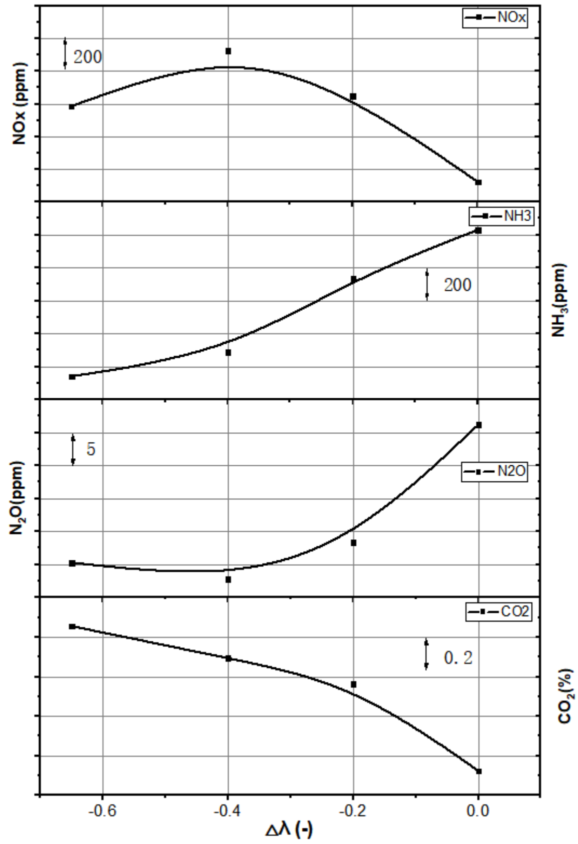


Figure 17 Effect of λ on emissions at 75% load with 70% AER

3.2.4 Optimization of diesel and ammonia injection parameter

The optimization of diesel injection parameters mainly includes diesel injection pressure and SOI_D. The effects on the combustion and emissions of ammonia mode are shown in Figure 18 to Figure 21, respectively.

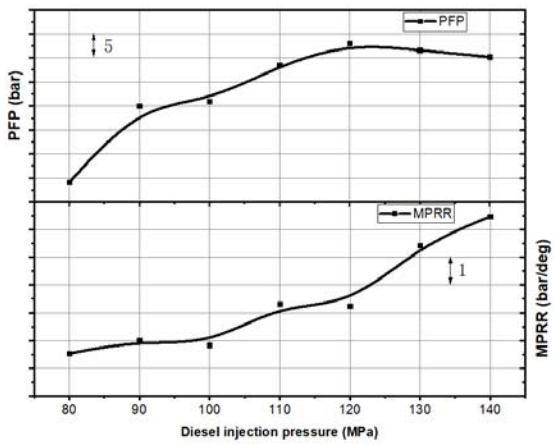


Figure 18 PFP and MPRR with different diesel injection pressure at 75% load with 70% AER.

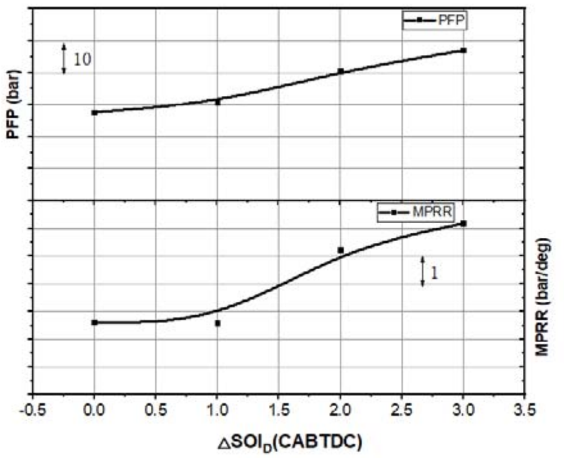


Figure 19 Impact of SOI_D on PFP and MPRR at 75% load with 70% AER.

Diesel injection pressure and SOI_D have a substantial impact on PFP and MPRR. The higher the injection pressure, the earlier the SOI_D, the higher the PFP, MPRR, and mechanical load. However, diesel injection parameters have a relatively small impact on ITE.

The increase in diesel injection pressure enhances the fragmentation and atomization of diesel, resulting in a more uniform mixture of diesel and ammonia premixed gas. This improved more ammonia is ignited and reduces unburned NH_3 emissions as rail pressure increases. However, when the rail pressure exceeds a certain threshold, such as 120 MPa under the studied conditions, the level of unburned NH_3 remains relatively constant. Relatively, SOI_D affects ammonia emissions to a lesser extent in the studied operating conditions.

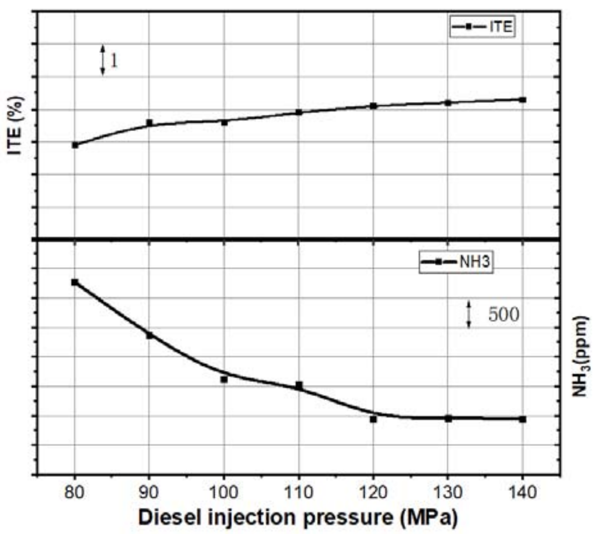


Figure 20 ITE and NH_3 emission with different diesel injection pressure at 75% load with 70% AER.

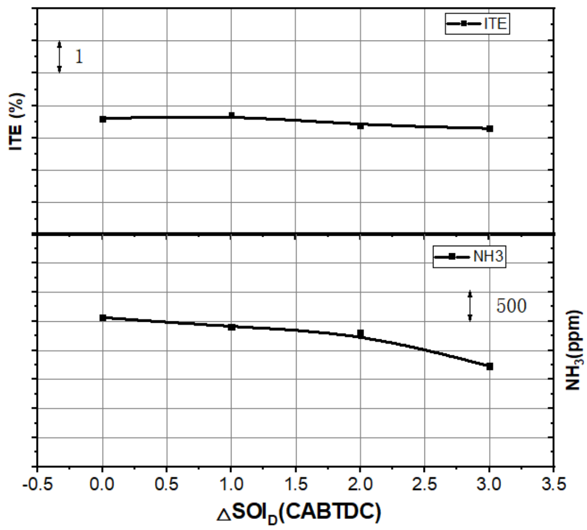


Figure 21 Impact of SOI_D on ITE and NH_3 emission at 75% load with 70% AER.

On the one hand, diesel injection parameters affect ammonia mode combustion and emissions. On the other hand, efforts should be made to minimize the differences between the two modes to optimize the mode switching process.

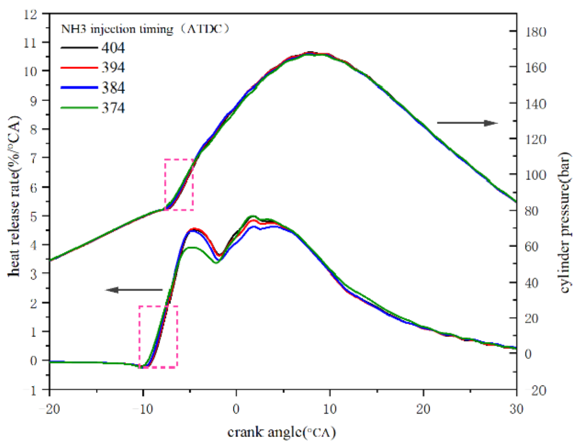


Figure 22 Effect of NH_3 injection timing on combustion[17]

Under the same AER, the ammonia injection pressure and duration have little effect on combustion and emissions, but the ammonia duration cannot be too long, otherwise it will cause incomplete injection within the intake valve opening range, resulting in an increase in unburned NH_3 emission. The timing of ammonia injection needs to be matched with the timing of the intake and exhaust valves to reduce ammonia escape in the valve overlap area. The detailed description of the NH_3 injection parameters on combustion and emission results are given in [17].

4 MULTI CYLINDER ENGINE

The test bench of 6CS27DF-A multi cylinder engine is as follows Figure 23. The engine performance development test was carried out in August of 2024. The test results are shown in Figure 24 and Figure 25.

Figure 23 6CS27DF-A multi cylinder engine test bench

Ammonia mode of CS27DF-A can be operated in the range of 20% to 100% load, and AERs higher than 70% can be achieved at different loads, with a maximum AER of 85% (Figure 24). The highest BTE in ammonia mode is close to 44% (Figure 25).

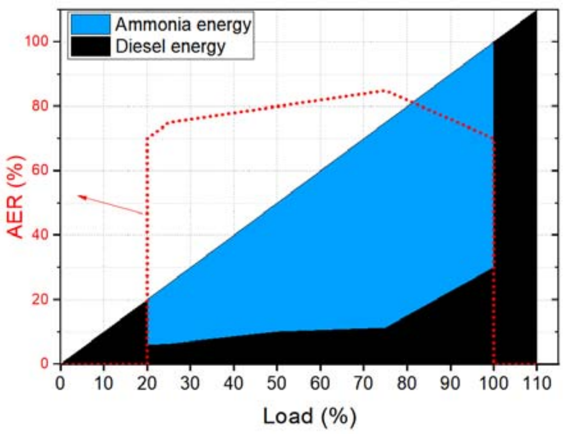


Figure 24 Engine operating map of a CS27DF-A ammonia dual fuel engine

The switching process of two combustion mode of CS27DF-A is shown in Figure 26. The engine is switched from diesel mode to ammonia mode, with speed fluctuations of less than ±10 rpm throughout the switching process and a duration of less than 30 s. The replacement rate reaches the target value (70%) in about 1 min. And switching from ammonia mode to diesel mode within 1s can be realized.

For ammonia engines, emission characteristics are of particular interest. CS27DF-A original emissions are shown in Figure 27. The maximum values of NH_3, NO_X, N_2O are approximately 9000ppm, 4000ppm, and 60ppm, respectively.

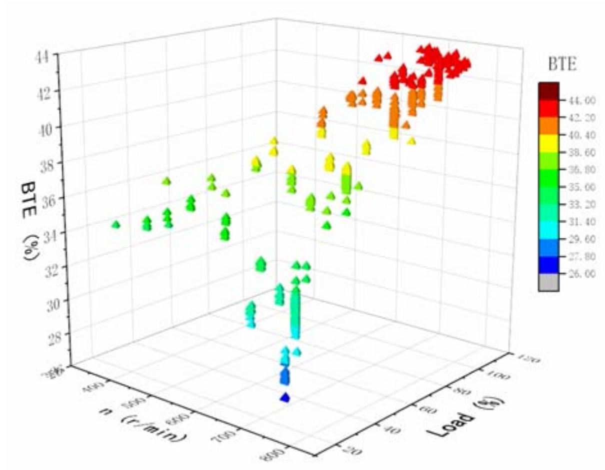
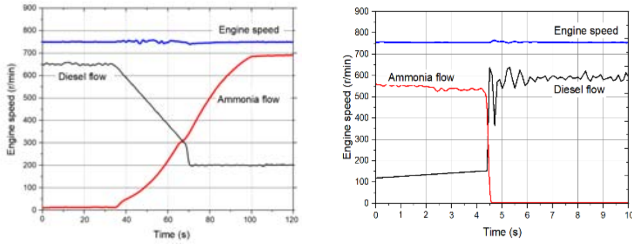


Figure 25 BTE of CS27DF-A ammonia mode of whole load.



(a) (b)

Figure 26 Switching process of two combustion mode. (a) Switching from diesel mode to ammonia mode (b) Switching from ammonia mode to diesel mode.

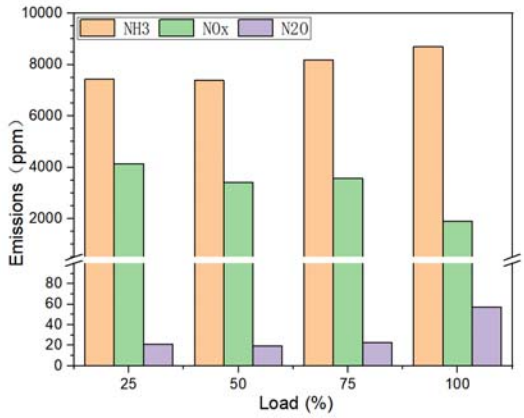


Figure 27 Emissions of CS27DF-A

The engine is equipped with SMDERI's own after-treatment unit, which meets the requirements of

Tier III regulations for NOx and has a treatment efficiency of over 96% for NH_3.

As of the time of writing this paper, the CS27DF-A had been running for over 600 hours, with the engine running well and all parameters stable.

5 SUMMMARY AND CONCLUSIONS

Ammonia is the most challenging but considered a highly promising carbon free fuel in the shipping industry.

SMDERI successfully developed CS27DF-A ammonia dual fuel engine. Combustion development was completed through ORCM and SCE, and parameters including AER, λ, fuel injection parameters, compression ratio, etc. were studied and determined, and the performance development of the multi cylinder engine was completed.

CS27DF-A can be operated at ammonia mode in the range of 20% to 100% load, with a maximum AER of 85%. The highest BTE in ammonia mode is close to 44%. By equipping post-treatment devices, various emission can be treated to meet the requirements of relevant regulations.

CS27DF-A can be use for propulsion for container, bulker, chemical products ships, offshore vessels, workboat & tugs and other types of river and coastal vessels; Auxiliary gensets for various ocean ships.

6 DEFINITIONS, ACRONYMS, ABBREVIATIONS

AER: Ammonia Energy Ratio

AFR: Air Fuel Ratio

ABS: American Bureau of Shipping

BMEP: Brake Mean Effective Pressure

BTDC: Before Top Dead Center

BTE: Brake Thermal Efficiency

CA: Crank angle

CA50: Crank angle where 50 % energy is released

CA90: Crank angle where 90 % energy is released

CCS: China Classification Society

CO_2: Carbon dioxide

DNV: Det Norske Veritas

DF: Dual Fuel

ECU: Electronic Control Unit

FTIR: Fourier Transform Infrared Spectrometer

GHG: Green House Gas

HPDF: High-Pressure direct injection Dual Fuel

IEA: International Energy Agency

IMO: International Maritime Organization

ITE: Indicated Thermal Efficiency

LPDF: Low-Pressure injection Dual Fuel

LR: Lloyd's Register

MPRR: Maximum Pressure Rise Rate

NH_3: Ammonia

N_2O: Nitrous oxide

NO_X: Nitrogen oxide

ORCM: Optical Rapid Compression Machine

PFP: Peak Firing Pressure

SMDERI: Shanghai Marine Diesel Engine Research Institute

SCR: Selective Catalytic Reduction

SOI_D : Start of diesel injection

SCE: Single Cylinder Engine

TDC: Top Dead Center

λ: The total air excess ratio of diesel and ammonia

7 ACKNOWLEDGMENTS

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