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# Fundamental study of the effect of stratified NH3 injection system for nitrogen compounds reduction

Emission Reduction Technologies - Exhaust Gas Aftertreatment Solutions

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## ABSTRACT

Green House Gases (GHG) reduction is unprecedented challenge marine industries have ever confronted with. In the research for high reduction in GHG, NH3 and H2 attract world’s attention as one of alternative fuels. Since these are carbon free fuels, adoption of these fuels for internal combustion engines is expected to be one of the promising solutions to lead a pathway towards carbon free shipping. Hence, we are working on the development of NH3 combustion engines and H2 combustion engines. Development of H2 combustion engine is in progress based on our experience, knowledge, and results of the Dual Fuel engine development. In this paper, the development status of the NH3 combustion engine is explained in detail.

As characteristics of NH3, it has high latent heat that cools the surrounding atmosphere at evaporation, high ignition temperature, which requires high ignition energy, slow combustion speed, and poor flame retention. In addition, from the combustion of NH3, N2O may be emitted, which has about 300 times higherã€€greenhouse effect than CO2.

To overcome these problems, Stratified Fuel Injection System with NH3 and diesel fuel oil is proposed to control the combustion of NH3. Spray from the Stratified Injection System has sandwiched layers of NH3 between diesel fuels. First layer (diesel fuel) acts as pilot fuel to ignite following NH3 layer and last layer (diesel fuel) contributes to the stable combustion of prior NH3 layer and also reduces NH3 slip and generation of N2O.

This paper describes detailed concept of stratified injection system with NH3 and diesel fuel and a strategy, which supports combustion of NH3, and is an effective solution for reduction of GHG emission.

As a fundamental research work, observations of spray formation and combustion tests are carried out to confirm the effect of this system using a newly developed constant volume combustion chamber that simulates the condition of a real engine. The data is useful to complete the design of low-speed two-stroke engine applying this system.

## 1 INTRODUCTION

To reduce greenhouse gas (GHG) emissions, hydrogen (H2) or ammonia (NH3) has recently gained an attention as a carbon-free fuel for internal combustion engine.

In case of using ammonia as fuel, there are disadvantages compared to fossil fuel due to the characteristics. It has high latent heat that cools the surrounding atmosphere at evaporation, high ignition temperature, which requires high ignition energy, slow combustion speed, and poor flame retention. In addition, from the combustion of NH3, nitrous oxide (N2O) may be emitted, which has about 265 times higher greenhouse effect than CO2 [2].

To solve these problems, Japan engine corporation (J-ENG) is developing a stratified ammonia injection engine that injects fuel oil (FO) and ammonia in a stratified manner. “FO” includes heavy fuel oil, gas oil, low sulfur oil or hexadecane, such as used as diesel oil. The concept is to apply J-ENG's existing stratified water injection technology to inject liquefied ammonia into the engine.

This allows the first FO layer (pilot FO) to act as an ignition source, efficiently combusting the ammonia that is subsequently injected. Furthermore, the combustion activation by the terminal FO (post FO) can reduce the production of unburned ammonia and N2O.

Currently, J-ENG is preparing an experiment using the single cylinder test engine. It is designed based on knowledge of previous studies [2][3]. It is financially supported by Japanese Government, Namely, Green Innovation Fund of New Energy and Industrial Technology Development Organization (NEDO).

In this paper, we will present previous studies [2][3] as a basic study of stratified ammonia injection. In the reference, direct imaging of the spray flame and shadowgraphs of the non-combustible spray were taken. In the direct imaging of the spray flames, it is confirmed that the strong luminescence is observed at the early stage of combustion. At the middle stage of combustion, luminescence area was not observed, but luminescence was re-observed at the end stage. It has relationship with the timing of post FO injected. In the non-combustion spray experiments, the spray shape of the ammonia layered spray is found to be similar to the spray outline shape of the FO spray.

In addition, we report the results of Rate of Heat Release (ROHR) and exhaust gas analysis of combustion test using hexadecane as FO in a visual constant volume combustion vessel (VCVCC).

## 2. CONCEPT OF STRATIFIED INJECTION

J-ENG has designed a stratified ammonia injection system by applying its existing stratified water injection technology. The stratified water injection system is a NOx reduction technology by injecting a fuel oil (FO) and water at once to lower the temperature during combustion. Focusing on the point of injecting FO and a different liquid at the same time, we thought that if ammonia was liquefied, the technology could be converted to a fuel injection system that injects FO and ammonia at the same time.

There are other advantages of stratified injection of FO and ammonia: the layer of FO on the tip side can be used as a pilot FO and as an ignition source for ammonia. Furthermore, the layer of FO on the terminal side can be expected to improve ammonia combustion at the end of the combustion period and reduce slip ammonia and N2O production.

Pilot injection of FO for diesel combustion of fuels with high self-ignition temperatures such as methanol or LPG has been used in the past, but the stratified ammonia injection is characterised by that such pilot fuels are injected again (post-injection) at the end of the ammonia injection duration.

Figure 1 shows the reaction temperatures at which each emission is formed in the flame as investigated by Okafor et al [1] using an experimental combustion apparatus. According to the figure, the formation temperature range of N2O is found around 1300 K. That is a lower temperature range than the normal FO whose flame temperature is above 2000 K.

In this figure, the peak of N2O production is lower than in other emissions, but considering the global warming potential of about 265 times that of CO2, it is necessary to avoid this temperature range and to ensure that N2O is reduced to as low as possible.

It is imagined that post-injection by means of the stratified ammonia injection system, it may be effective in reducing not only unburnt ammonia but also N2O, by activating the ammonia spray flame again and raising the flame temperature.

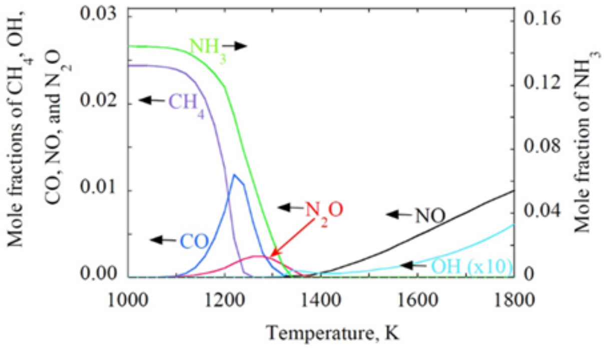

Figure 1. Profiles of emissions in the oxidation of CH4-NH3-air mixtures (ENH3 =0.7, ϕ = 1.1) in a laminar plug flow reactor at various oxidation temperature and a constant arbitrary residence time of 0.3 s [1]

In actual operation, an ammonia injection channel is connected to the middle of the FO channel inside of the injector. Schematics of stratified ammonia injection system in actual engine is shown in Figure 2. It consists of fuel oil pump, fuel injection valve and ammonia injection pump.

Figure 3 shows working procedure of the stratified ammonia injector.

(A) Before the start of injection, FO channel inside of the injector is filled with FO. Ammonia is filled up to the connection of FO channel.

(B) Ammonia discharged from the ammonia injection pump forms a layer, of FO and ammonia inside of the FO channel.

(C) To inject stratified FO and ammonia, fuel oil pump discharges FO. Then, the FO and ammonia in the FO channel are pushed and injected into the engine. At first, FO is injected so it behaves as pilot FO. After that, ammonia is injected continuously.

(D) As the fuel oil pump continues injection, all ammonia that was filled inside of the FO channel will be injected. At the end of injection, FO is injected as post fuel.

The quantity of ammonia can be controlled by actuating the lift of the ammonia injection pump, and the total amount of FO and ammonia can be controlled by actuating the lift of the fuel oil pump, thus controlling the total heat value and ammonia calorific ratio.

Figure 4 shows a simple CFD simulation on the spray formation process of the fluid injected as described above. The red and blue fluids are assumed to be FO and the yellow fluid ammonia.

Figure 4(a) shows that the red pilot FO injected first is pushed out to the periphery of spray by the following yellow ammonia. This is advantageous as the ammonia could be ignited by multi-points from the periphery of spray.

Figure 4(b) shows the last part of injection. The blue colored post FO is injected after the yellow colored ammonia. It can be seen that the post FO penetrates into the central part of spray by its own momentum. It is supposed that the post FO could activate combustion from internal region of the ammonia spray. As a result, post FO is expected to be effective in reducing unburnt ammonia and N2O production as discussed later.

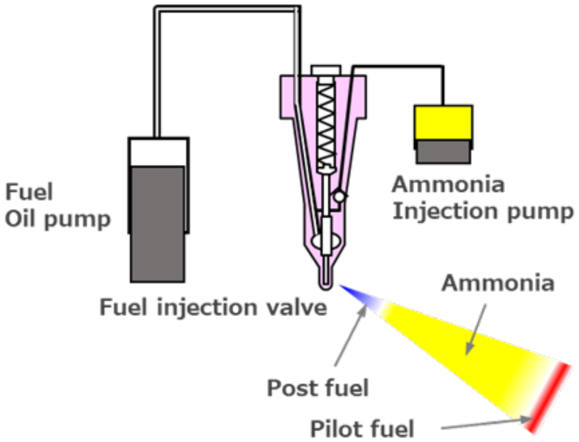

Figure 2. Schematics of stratified ammonia injection system in actual engine.

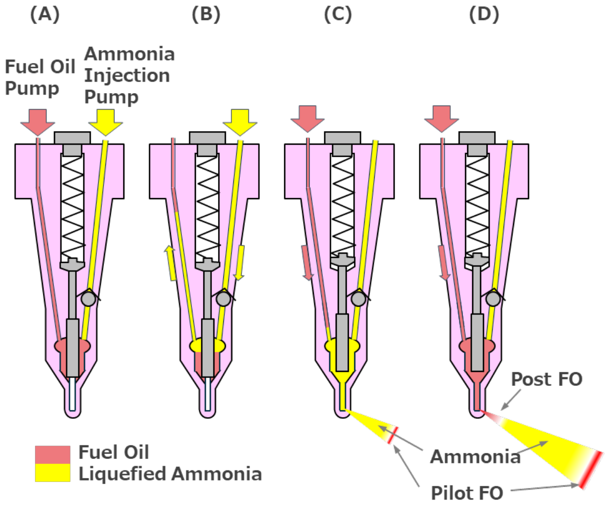

Figure 3. Working procedure of the stratified ammonia injector.

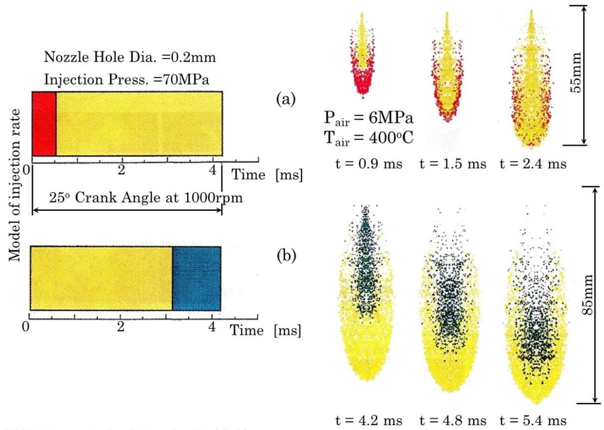

Bild 5: Computersimulation der Strahlbildung
*Fig. 5: Numerical results of the spray characteristics*

Figure 4. CFD analysis result of Stratified Injection.

## 3. EXPERIMENTAL SETUP

To verify the effect of our combustion concept, a visual constant volume combustion vessel (VCVCC) was developed to simulate combustion in the cylinder of a large two-stroke marine engine.

Figure 5 shows the appearance and cross-sectional view of the VCVCC, fabricated to conduct basic combustion experiments for stratified injection combustion. The distance from the injection hole to the bottom of the combustion space was 350 mm, and the diameter of the combustion space was 150 mm. During the visualization test, an observation window of 300 mm long and 96 mm wide was installed. The in-chamber pressure was measured using a water-cooled in-cylinder pressure sensor (Kistler, 6041 B). The heat release rate was then be calculated from the in-chamber pressure history [3].

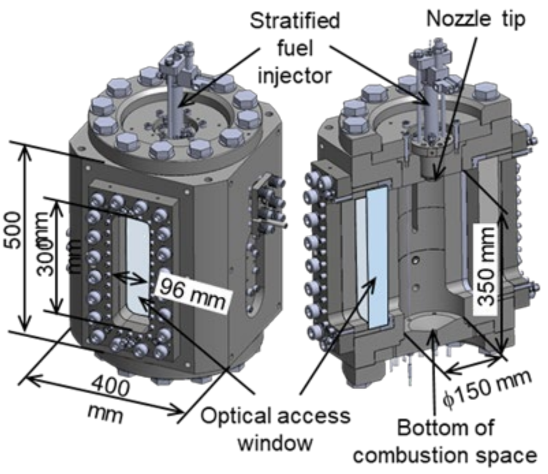

Figure 5. Schematics of the exterior and cross-section of VCVCC [3].

Figure 6 shows the entire experimental combustion system. Air supplied from a high-pressure air source at a controlled flow rate is heated by a heater and filled into a heated vessel. When the inside of the vessel reaches the target pressure, it is sealed. FO is then injected and a combustion experiment is conducted. 100 milliseconds after the injection signal is issued, the exhaust valve is opened to release the combustion gas into a buffer tank that has been evacuated in advance. This rapid depressurization freezes the chemical reactions in the VCVCC. The composition of the combustion gas in the buffer tank is analysed by Fourier transform infrared spectrometer (FTIR) analyser (Iwata Dengyo, Fast-2200) [2].

Figure 7 shows schematic of the NH3 stratified injection system of VCVCC test system. The system primarily comprises a fuel injection pump of a pressure-amplifying piston type, a stratified fuel injector, and an NH3 supply unit. The fuel injection pump can adjust the injection pressure by controlling the working oil pressure and injection period, by manipulating a high-speed hydraulic servo valve. The stratified fuel injector has the flow channels for the FO and liquid NH3. The liquid NH3 supply unit can charge the required volume into the FO flow channel. In addition, the fuel injection pump and stratified fuel injector are equipped with Non-return Valve 1 for the FO and Non-return Valve 2 for the NH3, respectively. The spray tip of the injector featured a single hole with a diameter of 0.7 mm [2].

Figure 8 shows appearance of test system, schematics are shown in Figure 5.

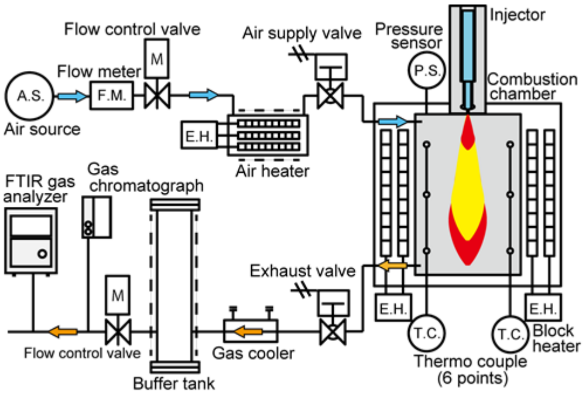

Figure 6. Schematics of the experimental combustion system [2].

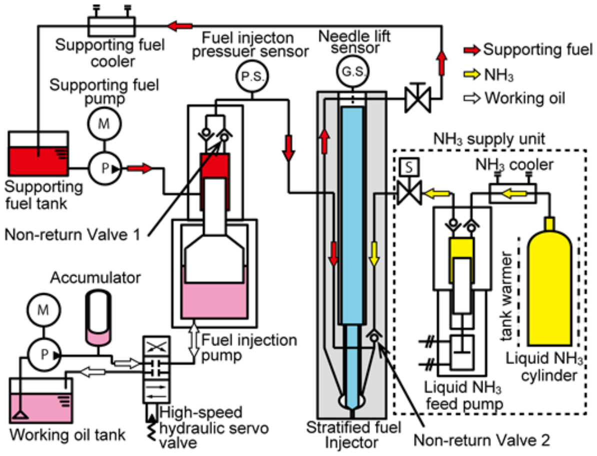

Figure 7. Schematic of the NH3 stratified injection system [2].

Figure 8. Photograph of VCVCC

## 4. EXPERIMENTAL RESULT

### 4. 1. Spray test, spray volume measurement

Figure 9 shows three patterns of energy injection rates, and Figure 10 shows three patterns of volumetric injection ratio. Details of the injected mass measurement system is shown in previous studies [2]. In this section, we will re-introduce the measurement method of injection rate.

The energy injection rates in terms of the lower heating value of the FO and liquid NH3 were estimated using the injection mass measurement results at several injection periods during one NH3 stratified injection. The stroke volume of the liquid NH3 feed pump was fixed in advance. The injection period could be controlled by a high-speed hydraulic servo valve, as shown in Figure 7 [2]. The actual injection period was measured by the needle lift sensor, as shown in Figure 7 [2].

In Case (A) shows the two-layer NH3 stratified injection of the FO / liquid NH3. There is a pilot FO at the tip, it contains higher injection energy of FO than injection energy of ammonia. After that, the FO fraction gradually decreases at the middle of injection period, and lower FO fraction continues at the end of injection period. The total injection energy of FO and ammonia is 51 kJ at the end of the measurement range.

In Case (B) (C), in which the NH3 injection volume is decreased, the presence of FO at the tip and the decrease of FO fraction at the middle of injection period are the same as that in Case (A). There is the difference from Case (A) in that the FO fraction increase at the end of injection. Finally, there is higher fraction of FO on the terminal side, which means combustion will proceed with post FO, so production of unburned ammonia and N2O will decrease compared with the Case (A). The total FO and ammonia injection energy of Case (B) is 55kJ and of Case (C) is 57 kJ.

The total NH3 energy ratio of Case (A) was 64%, Case (B) was 54% and that of Case (C) was 49% in one NH3 stratified injection [2].

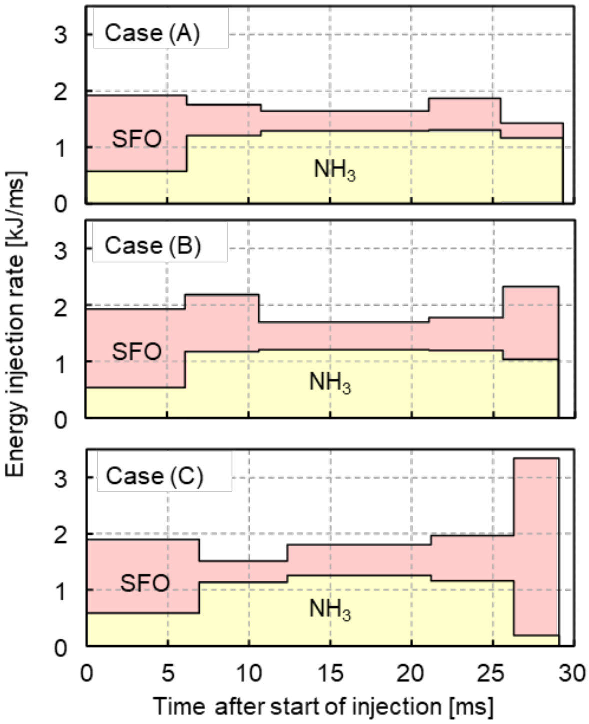

Figure 9. Three patterns of energy injection rates. Modified from [2].

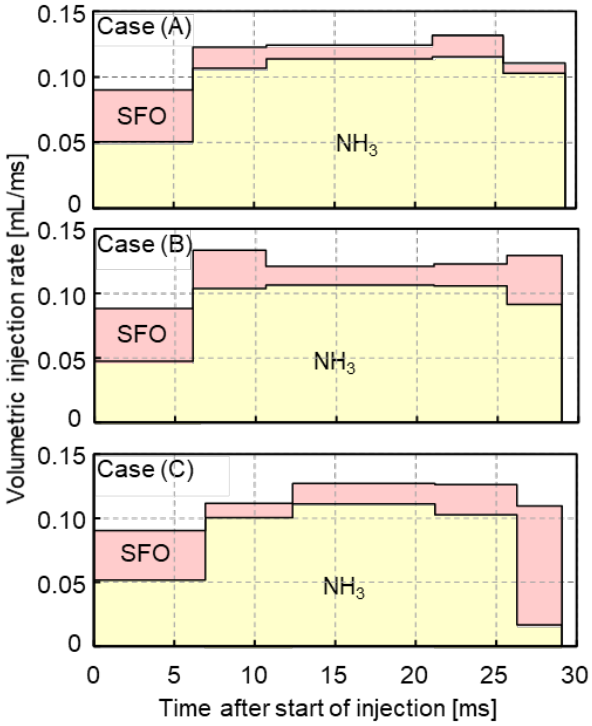

Figure 10. Three patterns of volumetric injection rates.

## 4.2. Referral of direct imaging

Visualization tests were performed using hexadecane as FO; visualization of FO-only injection and visualization test results for stratified ammonia injection are shown.

In the FO-only visualization test result is shown in Figure 11. In this result, luminesced flame was observed at 9ms after start of injection. After that, the area of combustion increases and combustion progresses.

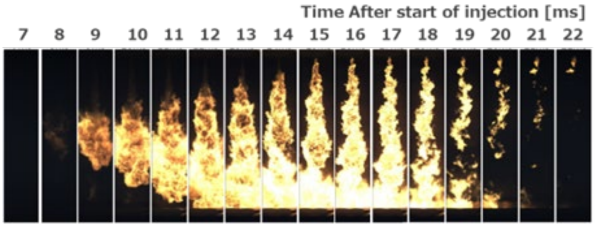

Figure 11. High-speed direct images of FO-only spray flame.

In the case of ammonia stratified combustion, injection rate of Case (B) is shown in Figure 12. The first luminescence is seen at about 2.5 ms. It sees that the pilot FO ignited at this timing. Subsequent flashes continue until about 18 ms. The color of the luminescence is orange, different from the color of the flame when only the FO is visualized, and is thought to be caused by the combustion of ammonia.

No luminescence is observed from 18 ms to 28 ms after start of injection. This is a period of low Rate of Heat Release (ROHR) discussed in section 4.3. , and ammonia combustion seems to be continuing, although not to the extent that luminescence is observed. After that, luminescence is seen again. The bright flame is seen in the area close to the injector, and orange luminescence is seen in the area farther away. It is thought that the ammonia is burning off assisted by the luminescence and ROHR from the post-FO and the combustion of the post-FO.

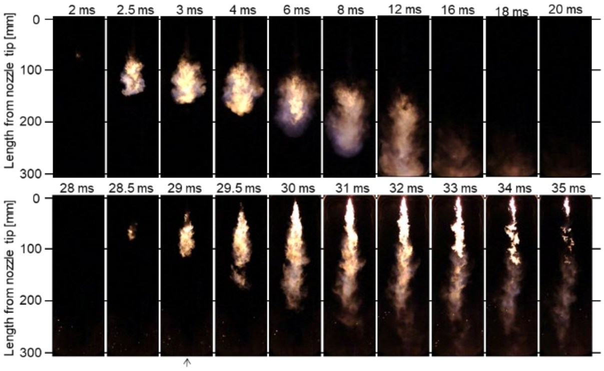

Figure 12. High-speed direct images of ammonia stratified spray flame. Modified from [3].

The results of the shadowgraphs for the non-combustion condition are shown in Figure 13. Case (S) shows the shadowgraphs of FO-only spray. The spray cone shape and spray length are generally the same for the FO-only case and the ammonia stratified injection case.

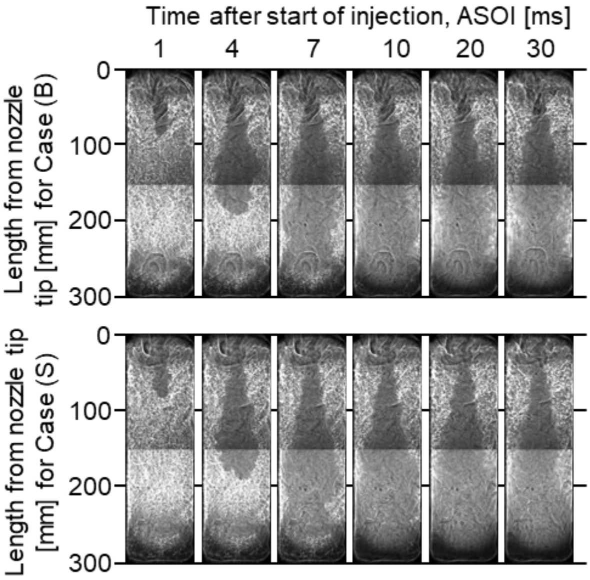

Figure 13. Shadowgraph images of ammonia stratified spray and FO-only sprays under non-combustion conditions.

### 4.3. Combustion test

A stratified combustion test was conducted using hexadecane. Results are shown for hexadecane-only, for NH3 pump stroke 40 mm (Case (A): ammonia calorific ratio is about 64%). NH3 pump stroke 20 mm (Case (B): ammonia calorific ratio is about 54%), NH3 pump stroke 15 mm (Case (C): ammonia calorific ratio is about 49%), where the injection volume was measured at 4.1.

In this experiment, pressure and temperature condition in VCVCC is 5 MPa and 783 K. This temperature is lower than that of the typical large marine 2-stroke engine, and the condition is severe for ammonia combustion with increased production of unburned ammonia and N2O. This experimental condition also causes reduce of ignitability, we use hexadecane as FO, which has good ignition properties, to ensure a stable experiment.

Figure 14 shows relationship between in-chamber pressure and heat release rate with respect to time after start of injection for Case (S), Case (A) and Case (C).

In Case (S), ROHR curve has mountainous waveform with a single peak. It is similar to commonly seen in typical conventional engines.

In Case (A), which has the higher ammonia fraction in all period of injection, there is a large ROHR peak in the early period, which appears to be due to the pilot FO combustion. At the middle period of combustion, the ROHR is lower than the early period. In this section, ammonia, which has a lower calorific value than FO, is injected. The ROHR does not reach zero. It indicates that combustion continues even higher fraction of ammonia, without support of FO combustion. After that, clear ROHR peak was not observed. The ROHR of terminal period decrease gradually. Heat release continues at about 50 ms after start of injection. At this time, the injection rates measurement result indicates that ammonia injection has already ended.

Figure 15 shows relationship between total of NO and NO2 (NOx) production ratios with respect with NH3 calorific ratio. Figure 16 shows relationship between N2O production ratios with respect with NH3 calorific ratio. Figure 17 shows relationship between NH3 production ratios with respect with NH3 calorific ratio. In the exhaust gas Case (A), unburned ammonia is about 0.03 mg/kJ and N2O is about 2.3 mg/kJ. These data indicate that ammonia still remains in the VCVCC and that the combustion is still continuing, even after the injection is terminated. This state is regardless of whether the FO is also remaining in the VCVCC or not.

It was confirmed that the stratified ammonia injection system enables the pilot FO to ignite the ammonia, and that even if the temperature drops due to the heat of vaporization when ammonia is injected. Ammonia combustion continues even without FO combustion support, although it burns at a slower rate for a longer duration.

Case (C) is a pattern in which the ammonia fraction decreases at the end period of injection, resulting in conditions in which post FO was expected to stimulate combustion and suppresses unburned ammonia and production of N2O.

There is a ROHR peak in the early period and lower ROHR at the mid period of combustion. Trend of ROHR of early period and middle period is almost same as Case (A). However, there is a second peak of ROHR not seen in Case (A) at 30ms after start of injection. From the results of the injection volume measurement test, this is the period of little bit after FO injection ratio increases and injection finished. Therefore, this second peak of ROHR seems to be caused by the post FO combustion. After that, heat release drops to almost zero rapidly, so burnable substances such as ammonia or FO are not remaining.

In the exhaust gas result, unburned ammonia decreased to about 0.006 mg/kJ and N2O to about 0.1 mg/kJ. In conjunction with the result of ROHR, even in an environment where ammonia is in combustion, post FO ignition is not inhibited, and the desired effect, activating combustion, reducing unburned ammonia and N2O production, are achieved.

Returning to Case (A), this comparison with Case (C) recognises the importance of the presence of post FO in combustion optimization, as post FO supports the ammonia to burn up quickly and to reduce the unburned ammonia and N2O production drastically.

From these experimental results, J-ENG designed a fuel injection system that was CFD analysed and optimized. This is, an ammonia stratified injection system that increases the ammonia calorific ratio while retaining post FO with certainty. J-ENG is preparing the stratified injection system for examination in a test engine.

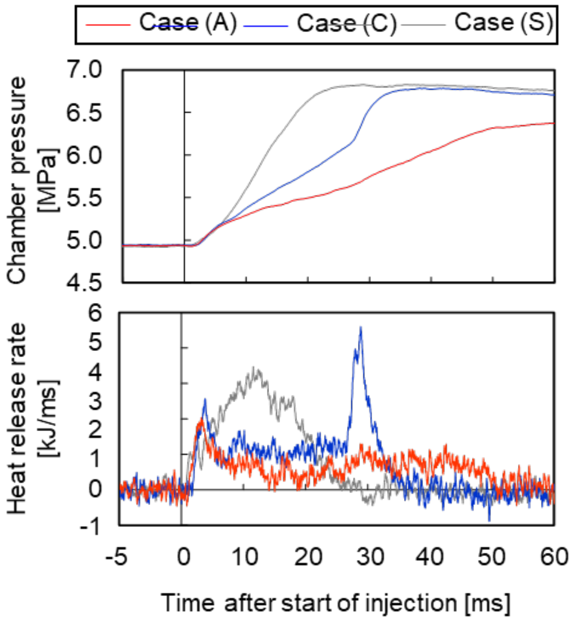

Figure 14. Relationship between in-chamber pressure and heat release rate with respect to time after start of injection. Modified from [2].

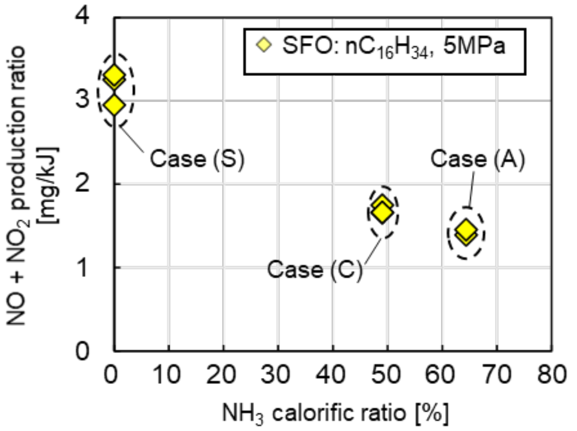

Figure 15. Relationship between total of NO and NO2 production ratios with respect with NH3 calorific ratio.

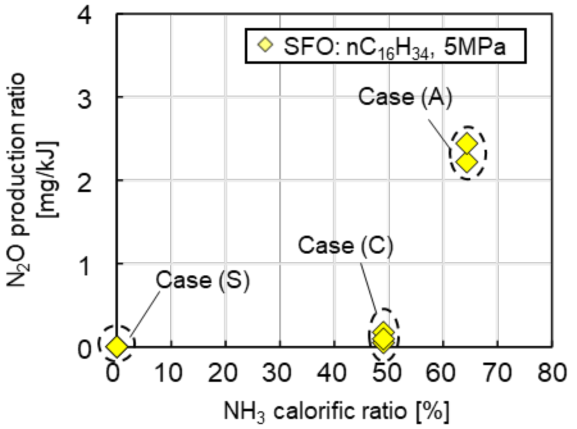

Figure 16. Relationship between N2O production ratios with respect with NH3 calorific ratio.

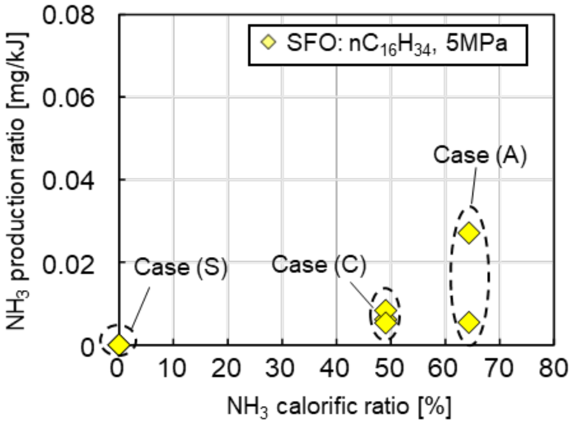

Figure 17. Relationship between NH3 production ratios with respect with NH3 calorific ratio.

## 5. CONCLUSION

A stratified ammonia combustion test and visualization test have been conducted by the newly developed VCVCC.

As a fundamental research work, observations of spray formation and combustion tests have been carried out to confirm the effect of this system using the VCVCC that simulates the condition of a real engine.

It has been confirmed that the first layer (FO) acts as pilot fuel to ignite following NH3 layer successfully and the last layer (FO) contributes to the stable combustion of prior NH3 layer and also significantly reduces NH3 slip and production of N2O.

In the case of two-layer injection, it is imagined that the combustion ends with the ammonia spray and the reaction of ammonia, which has lost momentum, proceeds slowly at a lower temperature, increasing N2O production.

On the other hand, if the after-burning part of ammonia is replaced by the last layer of FO, its spray penetrates the ammonia flame and burn the whole flame actively. Not only the higher temperature combustion, but also the H radicals produced by the combustion of the last layer may also contribute to N2O reduction by promoting the NO reduction reaction of NO + H = N + OH and the N2O consumption reaction of N2O + H = N2 + OH [2].

All the data is useful to improve the design of low-speed two-stroke engine applying this system. This successful low-emission cases was achieved by the VCVCC described above, where the ammonia calorific ratio was limited to about 50 - 60%, to ensure a stable experiment. This limitation is due to the lower temperature and pressure than that of the typical large marine 2-stroke engine.

The authors plan to carry out running tests with a test engine, which surely achieve the higher ammonia calorific ratio with improved combustion environment, optimized stratified injection system and superior control technology. The results of test engine will be fed back into the design of the full scale engine, which will be in service for the verification voyage after shop test completed.

## Acknowledgments

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## LITERATURE

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