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Ammonia combustion technology for a single-fueled spark ignition engine

New Engine Concepts & Systems

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ABSTRACT

Reducing greenhouse gas (GHG) emission is one of the most pressing issues in maritime industry and power generation. Therefore, ammonia fuel which is one of the carbon-free fuels is attracting attention. However, ammonia is difficult to combust due to its poor ignitability and slow combustion speed. Although most researchers are investigating the use of hydrogen which includes cracking from ammonia, hydrogen increases the knocking possibility. Hence, this paper describes the development of a single-fueled spark ignition ammonia engine, which no longer requires hydrogen assist.

First, improvement of the spark ignition for ammonia was carried out by using rapid compression and expansion machine. This test showed that flow strongly influences the ignition probability. So, pre-chamber plug (PC-plug), which can reduce the flow effect by covering the electrode with a cap, can improve the ignition of ammonia. Furthermore, using the optimized pre-combustion chamber (PCC) for the PC-plug mounted on this PCC can amplify the heat release at the initial stage of combustion initiated by the PC-plug. At the main stage of combustion, the PCC injects a powerful multi-jet flame into the main combustion chamber (MCC), so the combustion duration in the MCC can be reduced due to the multipoint ignition in the MCC. In addition, optimization of temperature, pressure, and equivalence ratio conditions are also important for a reliable ignition and the fast combustion of ammonia.

Finally, based on these fundamental test results, a single-cylinder engine test was carried out to demonstrate the possibility of the single-fueled spark ignition ammonia engine. In this test, it was found that residual gas in the PC-plug dramatically affects the ignition probability. This issue can be completely prevented by modifying the PC-plug and PCC to improve the gas exchange in the PC-plug. The engine test result demonstrates that ignition reliability and combustion duration are comparable with those of conventional LNG-fueled gas engines. As a conclusion of this study, the single-fueled spark ignition ammonia engine will be realized in the near future.

1 INTRODUCTION

Ammonia fuel is attention in maritime industry and power generation as an alternative fuel for reducing greenhouse gas (GHG) emissions [1]. For example, The International Maritime Organization (IMO) declared at the MEPC 80 meeting that its goal is to reduce GHG emissions by more than 20% within 2030, 70% by 2040, and 100% by around 2050, compared to 2008 levels. Amid the introduction of such regulations, classification societies predict that 20% to 40% of ships will be running on ammonia fuel by 2050 [2]. Ammonia burns slowly and requires a high amount of energy to ignite. For this reason, many developments are being carried out mainly by co-firing with other highly flammable fuels.

Ammonia-fueled engines have been developed based on both diesel engines and gas engines. Diesel-based ammonia engines are ignited by liquid fuel such as Marine Diesel Oil (MDO) [3-10]. IHI and IHI Power Systems (IPS) have developed an ammonia fueled engine based on a diesel engine with a fuel share ratio of up to 95% [11]. While this method is relatively easy to develop and retrofit, it is difficult to further reduce GHG emissions because fossil fuels are used as ignition agents at a certain rate.

On the other hand, ammonia engines based on gas engines that ignite by spark ignition are also being developed. In this system, zero GHG emissions may be achieved, without using hydrocarbon-based fuels and with suppressing N_2O emissions. Since ammonia has poor ignitability and flammability with spark ignition, co-firing with hydrogen (including those cracked from ammonia) has been studied extensively as a fuel that does not contain carbon and has good flammability [12-14]. However, hydrogen is too reactive, which increases the risk of knocking, pre-ignition, and backfire, and if hydrogen is produced by ammonia cracking, extra equipment is required for this purpose. This means it is more useful as an engine system to be able to burn with only ammonia. Such engines have also been developed, and it is known that there are conditions under which they can operate on ammonia alone [15-20]. However, most of these studies have been conducted on small engines, and there are few examples on medium-sized engines. In addition, the conditions under which engines can be driven are very limited.

Therefore, authors have developed a combustion technology with the aim of realizing an engine that can burn ammonia without the assistance such as hydrogen. In order to construct the system necessary for ignition and combustion of ammonia alone, methods and conditions that enable rapid combustion were searched for by element tests using a machine that can simulate the temperature and pressure in the combustion chamber of actual engine. This obtained method was applied to the single-cylinder engine test, and it was confirmed that ammonia can be burned alone in the engine.

2 DEVELOPMENT OF SINGLE-FUELED AMMONIA COMBUSTION TECHNOLOGY

2.1 Testing Methodology

To combust ammonia as an engine fuel, ignition technique must be clarified. To find a technology that can ignite an ammonia premixture without other fuels, a RCEM (Rapid Compression and Expansion Machine, Figure 1, and the specifications are shown in Table 1), which can simulate the temperature and pressure in an actual engine combustion chamber, was used.

The RCEM can hydraulically stroke the piston from bottom dead center to top dead center, which minimum compression time is equivalent to 540 min-1 of an actual engine. In order to achieve the target temperature and pressure at compression end, the charging pressure and temperature before compression and the compression ratio were adjusted. The mixture ratio of ammonia and air was controlled by mass flow controllers, and a homogeneous premixture was formed by a static mixer and then supplied into the combustion chamber before compression to achieve the target equivalence ratio. The downstream piping of the static mixer and the wall surface of the combustion chamber were heated to a temperature equal to the charging temperature.

The pressure in the Main Combustion Chamber (MCC) and Pre-Combustion Chamber (PCC) were measured by using a piezoelectric pressure sensor (MCC: AVL QC34D, PCC: GF11D). In-cylinder temperature was calculated from the in-cylinder pressure and the theoretic ratio of specific heat which could be estimated from the premixture composition by using NIST Chemistry WebBook [21]. Piston displacement was measured by using a laser displacement meter (Keyence LK-G405), and cylinder volume changing was calculated from the measured piston displacement.

The heat release rate is calculated from the pressure and volume changes of the MCC. Ignition delay was defined as the time from spark ignition to 5% of the total amount of heat release, and combustion duration was defined as the time from 5% to 90% of the total amount of heat release.

As shown in Figure 2, in this RCEM, there is a slight variation in operation during the repetitive operations because of the hydraulic system. Therefore, in this paper, repeated tests (3~10 times) were performed under the same conditions, and when showing the MCC and PCC pressure history and the heat release rate, each test case is superimposed to express the variation. In addition, although the data is organized based on the time when the TDC is reached, the ignition signal is issued a command based on the start time of the RCEM operation, so the ignition timing for the TDC also varies. The range of ignition timing for the TDC is shown for each test condition.

This RCEM has less turbulence in the MCC than the actual engine. Therefore, combustion in the RCEM will be slower than in an engine. Conversely, if the technology to burn ammonia at a sufficient speed for engine operation could be developed in RCEM test, it will ensure to achieve a sufficient combustion speed in an actual engine.

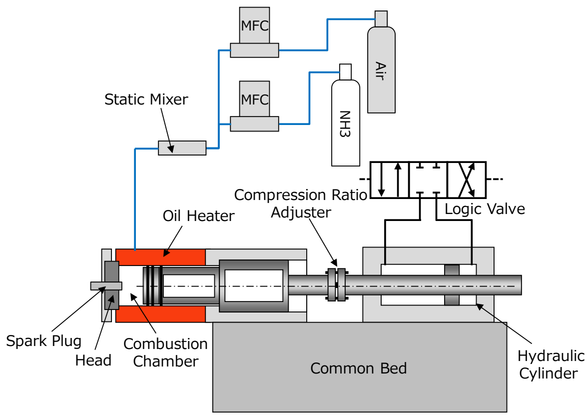


Figure 1. Schematic of the Rapid Compression and Expansion Machine (RCEM)

Table 1. Specifications of the RCEM

Bore	150 mm
Stroke	180 mm
Swept Vol.	3.18 L
Piston Speed (Equivalent to)	540 min^{-1}
Maximum Cylinder Pressure	20 MPa
Hydraulic Cylinder Force	370 kN
Hydraulic Pressure	21 MPa

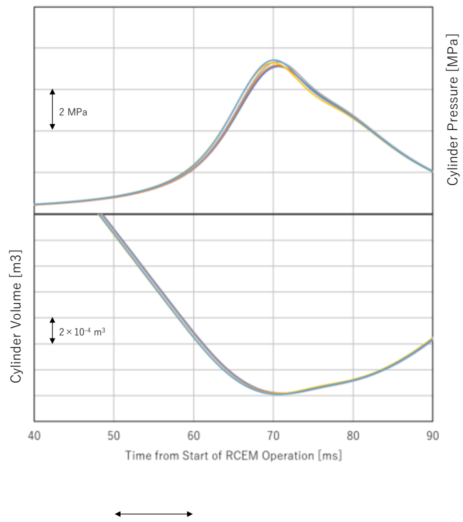


Figure 2. Example of the repeatability of the test (ahead: MCC pressure, bottom: Cylinder volume)

2.2 Effects of PCC

First, a method for burning ammonia at the speed required to run the engine was explored.

As a test, ignition by attaching a spark plug directly to the MCC was performed. The test condition is shown in Table 2. The pressure history and heat release rate are shown in Figure 3. Spark ignitions were executed at -4 ~ -2 ms after TDC (ATDC). Almost no heat generation is observed near the TDC immediately after ignition, and heat release begins only after it descends to the BDC, and the heat release is also very slow. It takes a very long time for heat generation to be clearly seen, and it seems difficult to burn completely in the vicinity of TDC with only a spark plug.

Table 2. Test conditions of open chamber spark ignition

Intake Pressure	260 kPa
Intake Temperature	116 deg.C
Mechanical Compression Ratio	13.8
Ignition Timing	-4 ~ -1 ms ATDC
Equivalence Ratio	1.0

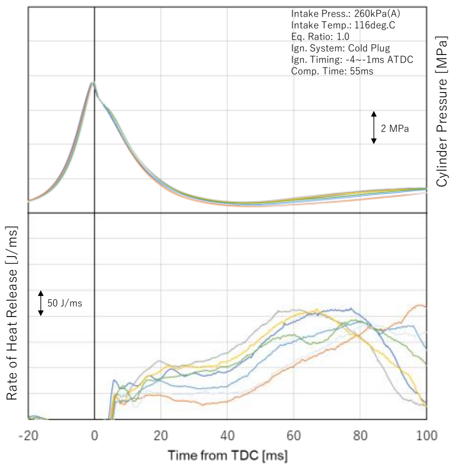


Figure 3. The pressure history and heat release rate of open chamber spark ignition

Thus, by using the pre-combustion chamber (PCC), which is often used in gas engines, the degree of shortening of the ignition delay and the combustion duration was confirmed compared to the case where the spark plug was installed directly in the MCC. The schematic diagram of the PCC used in Figure 4 is shown, and the test conditions are shown in Table 3. The intake pressure and temperature are the same as in the case of direct ignition. As with conventional gas engines, two types of ignition timing are set so that combustion in the PCC is completed before the TDC is reached. Since the piston position has not been changed, the mechanical compression ratio decreases and the compression end pressure decreases slightly as the total combustion chamber volume is increased by the PCC.

Figure 5 shows MCC pressure, PCC pressure and heat release rate when PCC is used, and Figure 6 shows a comparison of ignition delay and combustion duration. In the case where the PCC is used, the pressure rises clearly near the TDC, and both the ignition delay and the combustion duration were shortened. The use of PCC is also effective in shortening the combustion duration even in the engines that use only ammonia as fuel. However, as can be seen from both the pressure history and the heat release rate, the fluctuation of combustion is still large even when PCC is used. In particular, in the PCC pressure shown in Figure 5, the pressure rise around -4 ~ 0 ms ATDC represents the combustion in the PCC, but it can be seen that the combustion of the PCC fluctuates in the first place. Therefore, the first thing to consider is to suppress the combustion fluctuation in the PCC.

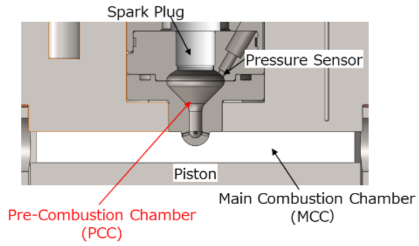


Figure 4. Schematic of the PCC attached to the RCEM

Table 3. Specifications of the PCC and test conditions when PCC is used

PCC Volume	5.5 cm3
PCC Hole	4 * 1.3 mm
Charging Pressure	265 kPa
Charging Temperature	116 deg.C
Mechanical Compression Ratio	13.1
Ignition Timing	-8 ms ATDC
Equivalence Ratio	1.0

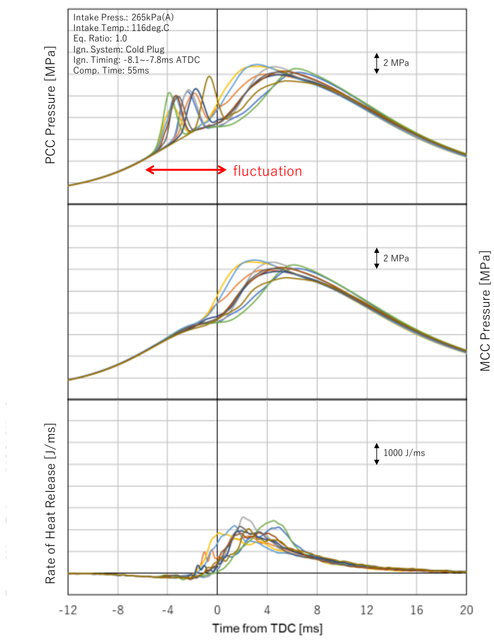


Figure 5. MCC and PCC pressure, and heat release rate when PCC is used

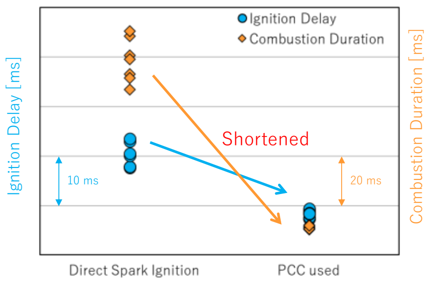


Figure 6. Comparison of ignition delay and combustion duration with and without PCC

2.3 Improvement Methods for Ammonia Single-Fueled Combustion

2.3.1 Suppression of Ignition Fluctuation in PCC by PC Plug

In general, the influence of flow pattern is also large on ignition, and it is thought that the influence is even greater in case of ammonia, which has low combustion ability. Therefore, to aim of reducing the fluctuation of combustion in the PCC by suppressing the flow near the electrode and stabilizing the ignition, a Pre-Chamber Plug (PC Plug) was used as a spark plug. The PC Plug is a type of spark plug attached with a cap with holes around the electrode of a normal spark plug, which can suppress the flow around the electrode and at the same time accelerate the combustion in the PCC by the burned gas jet ejected from the cap injection hole. A schematic diagram of a PC Plug is shown in Figure 7. The test conditions are the same as those shown in Table 3 except that the spark plug is changed.

Figure 8 shows the PCC and MCC pressure when burned using the PC Plug. In addition, Figure 9 shows a comparison of the maximum PCC pressure rise rate as an indicator of the combustion speed in the PCC. As shown in Figure 8, compared to the case of a normal spark plug (Figure 5), the fluctuation of the ignition in the PCC can be suppressed (around-5 ~ -1 ms ATDC). In other words, it can be said that the PC Plug contributes to the stabilization of ignition in the PCC. On the other hand, as shown in Figure 9, the combustion speed in the PCC did not increase even when the spark plug was changed to the PC Plug, and the heat release of the MCC also fluctuated. Although ignition is possible, the combustion of the PCC cannot be accelerated because the expected effect of combustion acceleration by the PC Plug is not obtained, and the production of burned gas cannot be also accelerated well in the PCC, which is considered to have an adverse effect on the combustion of the MCC.

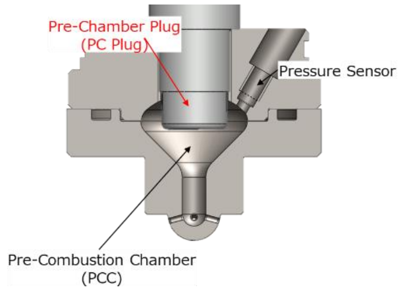


Figure 7. Schematic of the PC Plug attached to the PCC

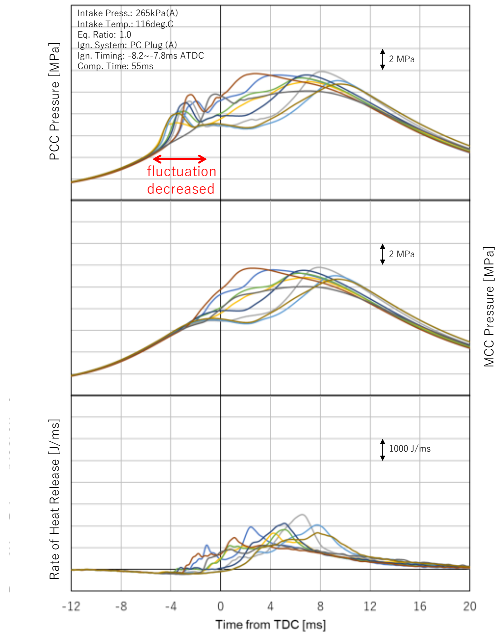


Figure 8. MCC and PCC pressure, and heat release rate when the PCC and the PC Plug are combined

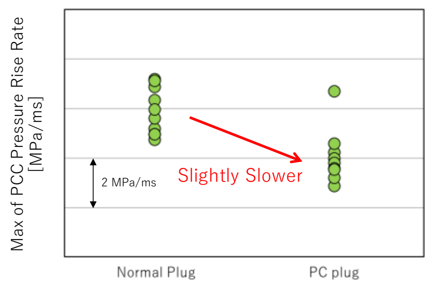


Figure 9. Comparison of the maximum PCC pressure rise rate in the PCC between the normal spark plug and the PC Plug

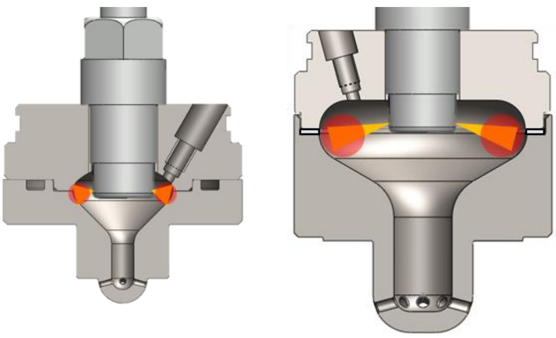
2.3.2 Matching of the Shapes between PCC and PC Plug

It was speculated that the reason for the lack of combustion acceleration effect in the PCC was the relationship between the shape of the PC Plug and the PCC. Figure 10(a) shows the arrangement of the PCC and the PC Plug, and a schematic diagram of the flame ejected from the PC Plug. The distance from the PC Plug hole to the wall is very short, and it is possible that the collision occurred before the gas jet developed. It is inferred that this is the reason the combustion promotion effect of the jet stream cannot be obtained.

Therefore, a new PCC with a space that does not interfere with the development of the jet flow ejected from the PC Plug was designed. Figure 10(b) shows a schematic diagram of the state of the gas ejection from the PC Plug. The test condition is shown in Table 4.

Figure 11 shows the MCC pressure, PCC pressure, and heat generation rate when tested with the newly designed PCC. Compared to the pressure of the original PCC (Figure 8), the pressure increase of the PCC is clearly larger, indicating that the combustion promotion effect of the PC Plug is obtained in large numbers. In addition, the pressure of the MCC rises rapidly, the heat release is larger, and the combustion stability is improved.

From this, by adopting a PCC shape that does not inhibit the development of the jet ejected from the injection hole of a PC Plug, the combustion promotion effect of the PC Plug can be obtained to a greater extent, which leads to stabilization and promotion of the combustion in the PCC and consequently in the MCC.



(a) Previous PCC (b) Matched PCC to the PC Plug

Figure 10. Images of the jet from the PC Plug, and of the PCC matched to the shape of the PC Plug

Table 4. Test conditions when the PCC matched to the PC Plug is used

PCC Volume	35 cm3
PCC Hole	8 * 2.5 mm
Charging Pressure	265 kPa
Charging Temperature	116 deg.C
Mechanical Compression Ratio	13.1
Ignition Timing	-7 ms ATDC
Equivalence Ratio	1.0

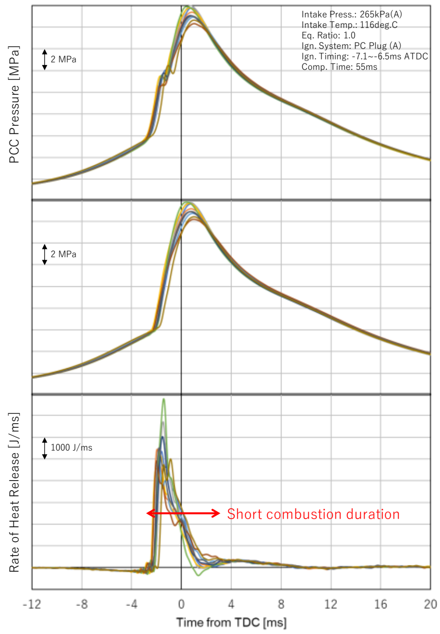


Figure 11. MCC and PCC pressure, and heat release rate when the PCC matched to the PC Plug is used

2.4 Effects of Pressure and Temperature to Ignition

In applying this method to an engine, it is expected that temperature and pressure will be required higher than those of conventional gas engines. Therefore, the minimum conditions required for ignition using this method were identified. The equivalence ratio was fixed at stoichiometry (1.0), assuming that ignition occurs near quantitative theory in real engines, and here pressure and temperature were evaluated. Table 5 shows the range of changes in temperature, pressure conditions at intake and at compression end, and ignition timing.

Figure 12 shows the success or failure of ignition organized by the temperature and pressure at the spark timing. It can be seen that the success or failure of ignition is greatly influenced by pressure. In the area indicated by the dashed line in Figure 12, cases of ignition and misfire are mixed, and ignition is generally successful at pressures above that, in contrast misfires are caused by less pressure. However, when the temperature is high, the threshold of the pressure for ignition decreases slightly. From this, it is assumed that a high compression ratio is required to increase the pressure, especially near the ignition timing. It is thought that the temperature can be increased automatically by increasing the compression ratio.

Table 5. Test conditions with various pressure and temperature

Charging Pressure	110 or 250 kPa
Charging Temperature	45 ~ 60 deg.C
Mechanical Compression Ratio	13.1
Ignition Timing	-8 ~ -3 ms ATDC
Equivalence Ratio	1.0

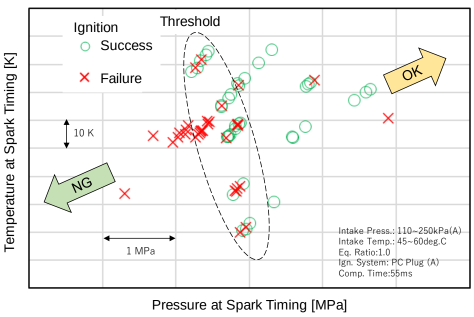


Figure 12. The success or failure of ignition organized by the temperature and pressure at the spark timing

2.5 The Specification of PC Plugs for Ignition Probability

The ignition and combustion conditions in the PCC may change depending on the shape of the PC Plug, which may affect the ignition and combustion of the MCC. In order to increase the certainty of ignition and combustion when applying this system which attaches the PC Plug in the PCC to engine tests, which leads to increasing the feasibility of ammonia-only fueled engines, a combustion test was conducted using different PC Plugs to investigate the effects on ignition and combustion in the PCC.

The specifications of the PC Plug used are shown in Table 6. The PC Plug used in the test so far corresponds to A in Table 6. The test conditions are shown in Table 7. It is generally the same as in Table 4, and only the pressure is lowered, in which condition the ignitability is more likely to differ.

Figure 13 shows an enlarged version of each PCC pressure near the ignition timing, and the number and probability of successful ignition are shown in Table 8. The probability of successful ignition of Shape D is significantly higher, and the fluctuation of the ignition timing at the time of successful ignition is also small. Although the cause of the phenomena will be considered in the future, in order to confirm the feasibility of ammonia combustion by engine tests described in the next chapter, it was decided to use a PC Plug with Shape D.

Table 6. Specifications of tested PC Plugs

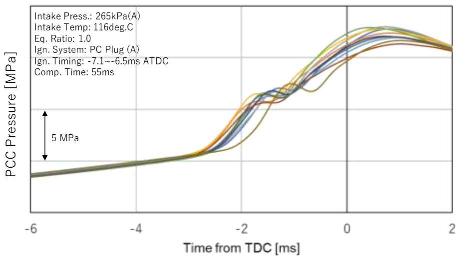
	Shape A	Shape B	Shape C	Shape D
Volume [cc]	1.6	1.6	1.0	1.2
Holes (num*diameter [mm])	5*1.7	7*1.2	4*1.2	5*1.3

Table 7. Test conditions when PC Plugs are changed

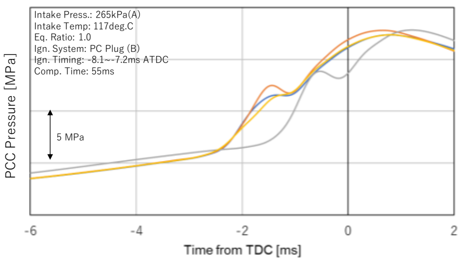
Charging Pressure	110 ~ 265 kPa
Charging Temperature	116 deg.C
Mechanical Compression Ratio	13.1
Ignition Timing	-8 ~ -3 ms ATDC
Equivalence Ratio	1.0

Table 8. The number and probability of successful ignition

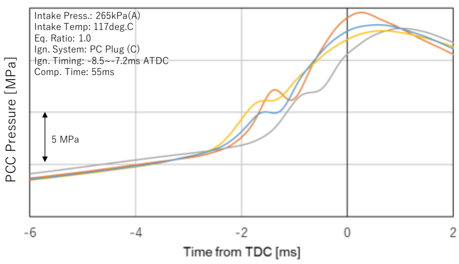
	Shape A	Shape B	Shape C	Shape D
Number of ignitions	40	28	33	50
Number of successful ignitions	29	15	20	49
Probability of successful ignition	73 %	54 %	61 %	98 %



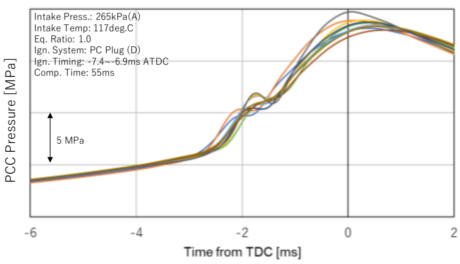
(a) Shape A



(b) Shape B



(c) Shape C



(d) Shape D

Figure 13. PCC pressure when PC Plugs are changed

3 VERIFICATION OF SINGLE-FUELED AMMONIA COMBUSTION TECHNOLOGY

The concept of the ignition system for ammonia combustion acquired in the previous chapter was applied to a single-cylinder engine (SCE), and the feasibility of a single-fueled ammonia engine was confirmed.

3.1 Testing Apparatus

Figure 14 shows a schematic diagram of the SCE used in the test, and Table 9 shows the specifications of the SCE. The air is supercharged by a electric compressor, and the ammonia used as fuel is continuously supplied by a mass flow controller. The original compression ratio of this engine was 11.2, but from the above study, it was found that pressure greatly affects whether ignition is possible, so the piston crown was changed to increase the compression ratio in order to meet the conditions required for ignition.

The arrangement in the combustion chamber is shown in Figure 15. Since it is not possible to install a PCC in the center of this SCE, the PCC is installed at the side of the combustion chamber, and the injector for pilot fuel injection is installed at the opposite side. When a stall occurs due to warm-up or misfire, pilot fuel is injected to perform diesel operation or DF operation. This SCE is connected to the AC dynamometer, and the rotational speed of the SCE is controlled by the AC dynamometer.

The data were obtained for 300 consecutive cycles of MCC and PCC pressure per condition. In this engine test, whether it was possible to operate with ammonia-only combustion was focused on, so IMEP, and COV of IMEP were paid attention to, and other detailed analyses were not conducted.

A new PCC was designed to realize ammonia combustion in this single-cylinder engine (Figure 16). Although the maximum diameter is smaller than that designed in the RCEM test due to the convenience of the mounting part, it was designed with the same concept as the one produced in the RCEM test, and the shape was designed to inhibit the jet flow generated from the PC Plug as much as possible.

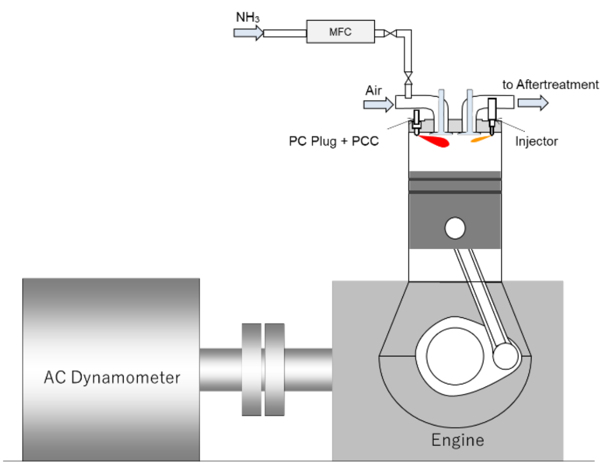


Figure 14. Schematic of the Single-Cylinder test Engine (SCE)

Table 9. Specifications of the Single-Cylinder test Engine (SCE)

Bore	180 mm
Stroke	200 mm
Displacement	5.1 L
Mechanical Compression Ratio	14.8
Rated Speed	750 min^{-1}

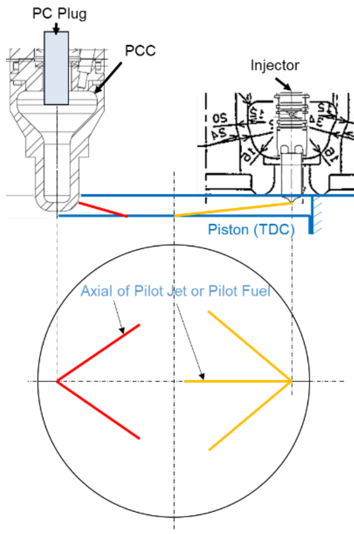


Figure 15. Schematic of the MCC of the SCE

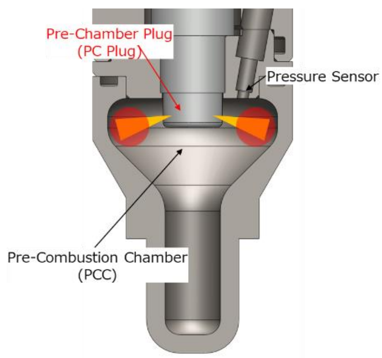


Figure 16. PCC for the SCE test

3.2 Testing Results

The test conditions are shown in Table 10. In this case, it would be good if it could be confirmed that the operation could be driven only with ammonia, so one condition is shown as a representative of the conditions under which the operation was actually possible. The rotation speed was 750 rpm, the IMEP was about 1.8 MPa (equivalent to 75% output), and the charge air pressure was adjusted so that the equivalent ratio was around 1.

Figure 17 shows the superimposed MCC pressure, PCC pressure, and heat release rate for 300 cycles, and Figure 18 shows the history of IMEP, as well as the average value and COV value. Although there was a slight fluctuation in the timing of the start of combustion, it was able to ignite and burn stably, and the SCE can be operated by spark ignition even with ammonia alone.

Since the Pmax reached the pressure resistance value of this engine under these conditions, it has not been possible to test the output further, but since it has been known from the previous chapter that the higher the pressure, the better the ignitability, it can be inferred that it will be possible to operate without problems even at 100 % output.

Next, the robustness when the intake pressure, equivalent ratio, and ignition timing were changed as parameters was ascertained.

Table 10. Test condition for confirming that the operation could be driven only with ammonia

Intake Pressure	210 kPa(A)
Spark Timing	-19.5 deg. CA ATDC
Intake Temperature	45 deg.C

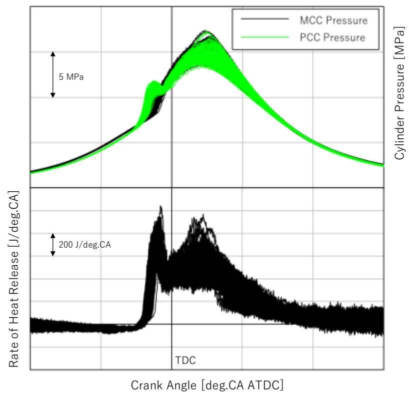


Figure 17. MCC pressure, PCC pressure, and heat release rate

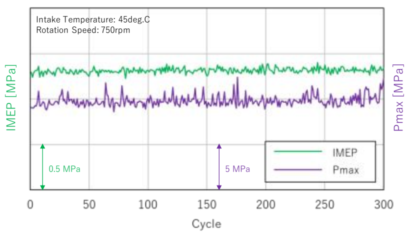
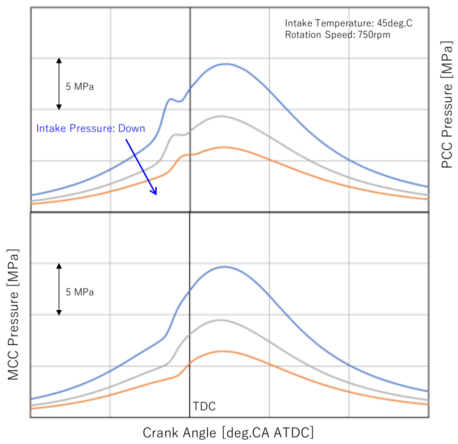


Figure 18. History of IMEP, and the average value and COV value of IMEP

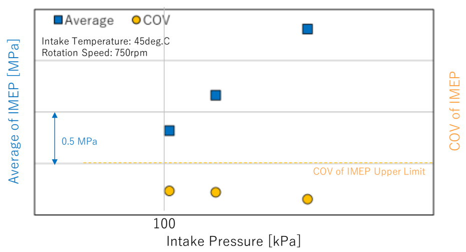
First, Table 11(a) shows the test conditions when the output is reduced by lowering the intake pressure while the rotation speed and the equivalence ratio are constant, and the average value of the MCC and PCC pressure, average and COV of IMEP for 300 cycles are shown in Figure 19. The lowest intake pressure condition is NA (equivalent to output 35%). Even if the pressure in the cylinder decreases, ignition and combustion can be performed without problems under any conditions, and stable operation is achieved.

Table 11. Test conditions when some parameters were changed

	(a) variable pressure	(b) variable spark timing	(c) variable equivalence ratio
Intake Pressure [kPa(A)]	variable	101	variable
Spark Timing [deg. CA ATDC]	-19.5	variable	-19.5
Equivalence Ratio	1.0	1.0	variable
Intake Temperature [deg.C]	45	45	45



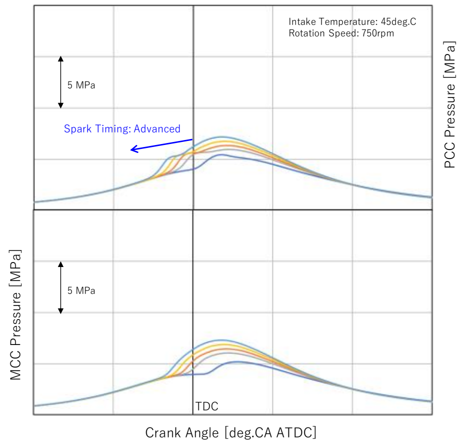
(a) Pressures in MCC and PCC



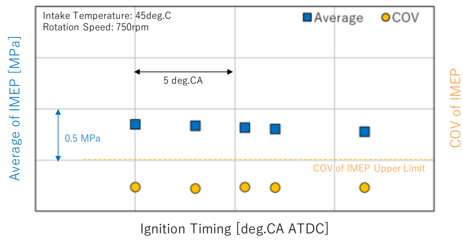
(b) Average and COV of IMEP

Figure 19. Average of MCC pressure and PCC pressure, and the average value and COV value of IMEP when intake pressure is varied

Table 11(b) shows the test conditions when the ignition timing is changed, assuming that the intake pressure and the equivalence ratio are constant, and the changes of the PCC and MCC pressure, average and COV of IMEP are shown in Figure 20. Since the fuel supply is constant and the thermal efficiency varies depending on the ignition timing, the IMEP varies slightly, but the operation is stable without misfiring at any ignition timing.



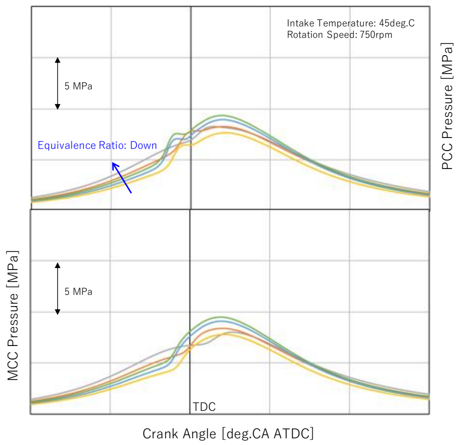
(a) Pressures in MCC and PCC



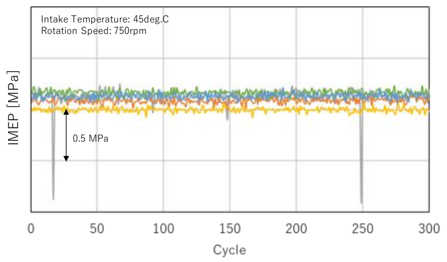
(b) Average and COV of IMEP

Figure 20. Average of MCC pressure and PCC pressure, and the average value and COV value of IMEP when spark timing is varied

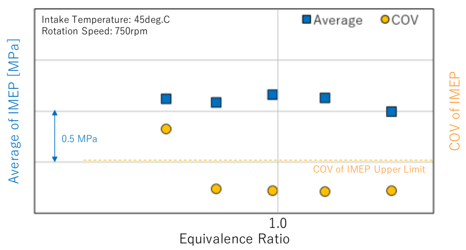
Table 12(c) shows the test conditions when the intake pressure is changed, which leads to changing the equivalence ratio, assuming that the supplied ammonia amount is constant, and the changes of the PCC and MCC pressure, average and COV of IMEP are shown in Figure 21. The COV of IMEP deteriorates under the condition with the lowest equivalence ratio, and combustion stability deteriorates. Equivalence ratio below this was not measured because misfired cycles increased. Combustion stability deteriorates in the region of approximately 0.8 or less of the equivalence ratio. Under this threshold, the pressure rise of the PCC was not observed in the misfire cycle, that is, the cause of the misfire was not the cycle fluctuation due to slow combustion, but the fact that combustion in the PCC could not be started in the first place. It is possible that the flame cannot be generated at the electrode gap of the PC Plug, or that it is burned in the PC Plug but not ignited in the PCC. In addition, since pilot gas is not supplied to the PCC in this test engine, the burned gas of the previous cycle remains in the PCC and in the PC Plug. This may also affect ignitability. The effect of the composition of the gas in the PCC or in the PC Plug on ignitability needs to be investigated in more detail. At least, it can be seen that stable combustion can be performed within a certain range of equivalence ratios even if it deviates from the stoichiometric ratio.



(a) Pressures in MCC and PCC



(b) History of IMEP



(c) Average and COV of IMEP

Figure 21. Average of MCC pressure and PCC pressure, and History of IMEP, and the average value and COV value of IMEP when equivalence ratio is varied

From these points, it can be said that it has been established as a robust system that can operate stably even if the parameters are changed to some extent, rather than under limited conditions as in the past research on ammonia-only fueled engines.

4 CONCLUSIONS

The system for igniting and burning ammonia independently was developed by testing with RCEM and confirmed the possibility of single-fueled combustion of ammonia in the engine by testing a single-cylinder engine. As a result, the following conclusions are drawn:

- As an ignition system, the combustion of the MCC can be accelerated by using the PCC, and the ignition of the PCC can be stabilized by using the PC Plug as a spark plug.
- By matching the shape of the PCC and the shape of the PC Plug, the combustion promotion effect produced by the PC Plug can be obtained largely, and the combustion of the PCC and thus of the MCC can be accelerated.
- Ignition probability is mainly determined by the pressure at the time of ignition, and if the pressure exceeds a certain level, the possibility of ignition increases greatly.
- It was shown that it could be operated by a single-cylinder engine. In addition, it was possible to operate stably even if the parameters were changed to some extent.

5 DEFINITIONS, ACRONYMS, ABBREVIATIONS

BDC: Bottom Dead Center

MCC: Main Combustion Chamber

PCC: Pre-Combustion Chamber

PC Plug: Pre-Chamber Plug

RCEM: Rapid Compression and Expansion Machine

SCE: Single Cylinder Engine

TDC: Top Dead Center

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