Development of Hydrogen and Ammonia Engine that Contributes to Decarbonized Society

YUSUKE IMAMORI*1 SOTA WATANABE*2
KENGO TANAKA*1 TOMOHIRO NOGUCHI*2
NAOYUKI MORI*3 SATOSHI YAMADA*4

In order to achieve a low-carbon and carbon-neutral society, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) is developing reciprocating engines that use hydrogen and ammonia as fuel. For hydrogen/natural gas mixed combustion engines, we verified with actual equipment the combustion characteristics when the ratio of hydrogen mixed with natural gas is increased to 35 vol%, and have clarified the conditions for avoiding abnormal combustion such as knocking and pre-ignition and determined specifications for future commercialization of the engine. For hydrogen combustion engines, we conducted numerical simulation and verification using a single cylinder testing engine to select operating conditions and component specifications that will achieve high power output and high efficiency while avoiding abnormal combustion, and are currently promoting the multi-cylinder engine design by developing the selected conditions and specifications. For ammonia/diesel oil mixed combustion engines to be used in marine engines, we researched for an appropriate combustion system that can significantly reduce greenhouse gases including N_2O *by using numerical simulation and have confirmed an 82% reduction compared to conventional engines through verification using a small test engine.*

1. Introduction

MHIET has been providing diesel and gas engines with excellent performance, reliability, and environmental characteristics for power generation, marine, and vehicle applications. In order to achieve a low-carbon and carbon-neutral society, we are developing triple hybrid power generation [(1)-(3)], adoptability of carbon-neutral fuels, and employment of CO_2 capture systems [(4), (5)] to further increase customer value with improvement of environmental characteristics and energy transition in mind [(6)]. This report introduces the development status of our new engines that use hydrogen and ammonia as carbon-neutral fuels.

As for hydrogen, we have determined the specification configuration and operating conditions of engines that can stably generate electricity using hydrogen mixed fuel without major specification changes to existing natural gas combustion engines. Furthermore, in order to realize stable combustion operation with 100% hydrogen fuel, we are developing hydrogen combustion engines with high efficiency and stable combustion without greenhouse gas emissions by utilizing flow and combustion numerical simulation technology.

As for ammonia, which is a promising carbon-neutral fuel for the shipping industry, we have determined operating conditions and component specifications that enable stable combustion of flame-retardant ammonia ignited by light oil while significantly reducing emissions of N_2O, which has a high greenhouse effect, and are currently working on further improvements. This report introduces the status of these developments.

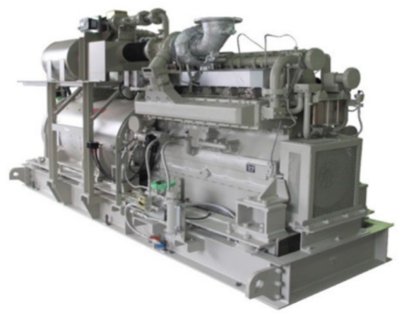
*1 Chief Staff Researcher, Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*2 Chief Staff Manager, Engine Technology Development Department, Engine & Energy Division, Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.
*3 Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.
*4 Manager, Combustion Research Department, Research & Innovation Center, Mitsubishi Heavy Industries, Ltd.

2. Development of hydrogen/natural gas mixed combustion engines

In Japan, a government policy of "aiming to achieve carbon neutrality by 2050" was presented. The use of hydrogen, which is the key to achieving carbon neutrality, may start with the use of hydrogen/natural gas mixture. Therefore, we worked with Toho Gas Co., Ltd. to develop a hydrogen/natural gas mixed combustion engine using our existing natural gas engine, and confirmed the impact on combustion performance when a hydrogen/natural gas mixture is used and the effect of reducing greenhouse gases (7).

2.1 Specifications of hydrogen/natural gas mixed combustion engine

For the test, we used the GS6R2, our leading gas engine model installed at Toho Gas's Technical Research Institute. The engine specifications were basically unchanged from those of the natural gas engine, and the adaptation was made by adding a hydrogen supply system. **Figure 1** shows the appearance and main specifications of the engine. The combustion system is pre-chamber type, which achieves stable lean combustion.



		GS6R2
Cylinder bore	mm	170
Stroke	mm	220
Rated rotation speed	min^{-1}	1 200
Number of cylinders	—	6
Rated output (generator end)	kW	450
Brake mean effective pressure	MPa	1.55
Combustion system	—	pre-chamber type lean combustion
Ignition system	—	Spark ignition

Figure 1 Appearance and main specifications of engine

Figure 2 shows the air and fuel supply system. The fuel supply line supplies a mixture of hydrogen and natural gas (city gas 13A) from upstream of the turbocharger. The mixing ratio is adjusted by a flow control valve installed in the hydrogen supply line. The power output in hydrogen/natural gas mixed combustion operation was set to 100% of the power output in natural gas operation.

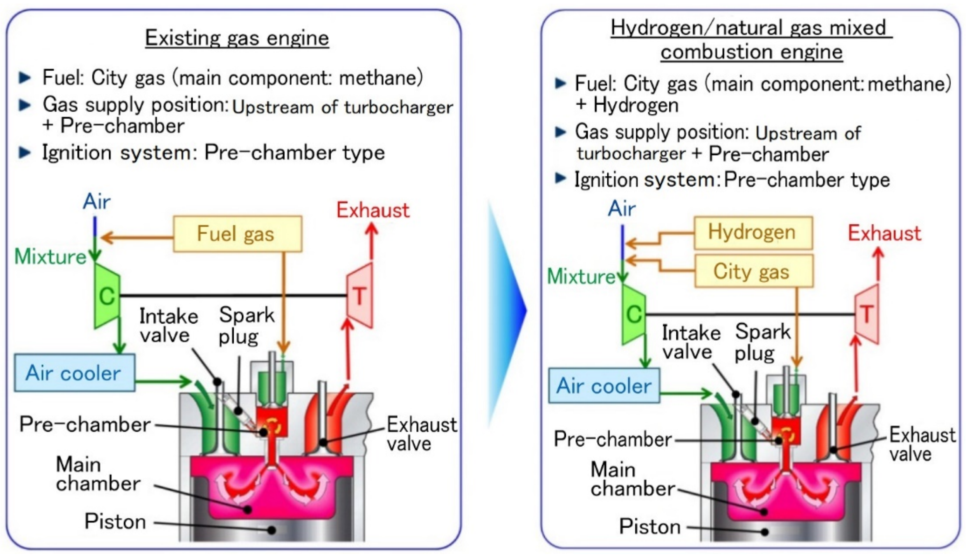


Figure 2 Air and fuel supply system (hydrogen/natural gas mixed combustion engine)

2.2 Test result of hydrogen/natural gas mixed combustion engine

Figure 3 shows the various engine performances when the hydrogen mixture ratio is increased with the air excess ratio and ignition timing kept unchanged. **Figure 4** shows the comparison of in-cylinder pressure and the rate of heat release for 0% and 35 vol% (12.5% in terms of heating value) hydrogen mixing. The vertical axis of each graph in Figure 3 indicates the ratio to the item at the base ignition timing and the hydrogen mixing ratio of 0%. Since hydrogen has a higher burning velocity than natural gas, mixing hydrogen accelerates the heat release, shortens the heat release period, and improves the degree of constant volume. As the heat release period shortens, the average in-cylinder gas temperature rises and the cooling loss increases due to the increasing temperature difference between the cooling wall surface and the gas, but the thermal efficiency improves due to the greater effect of improving the degree of constant volume. On the other hand, increasing the hydrogen mixing ratio also increases NOx emission concentration, so measures such as delaying the ignition timing and adjusting the air-fuel ratio are necessary.

Since knocking and pre-ignition are likely to occur when the hydrogen mixture ratio is increased, the specifications for commercialization will be determined after confirming the range of hydrogen mixture ratio and air excess ratio that can avoid the occurrence of these abnormal combustions through testing.

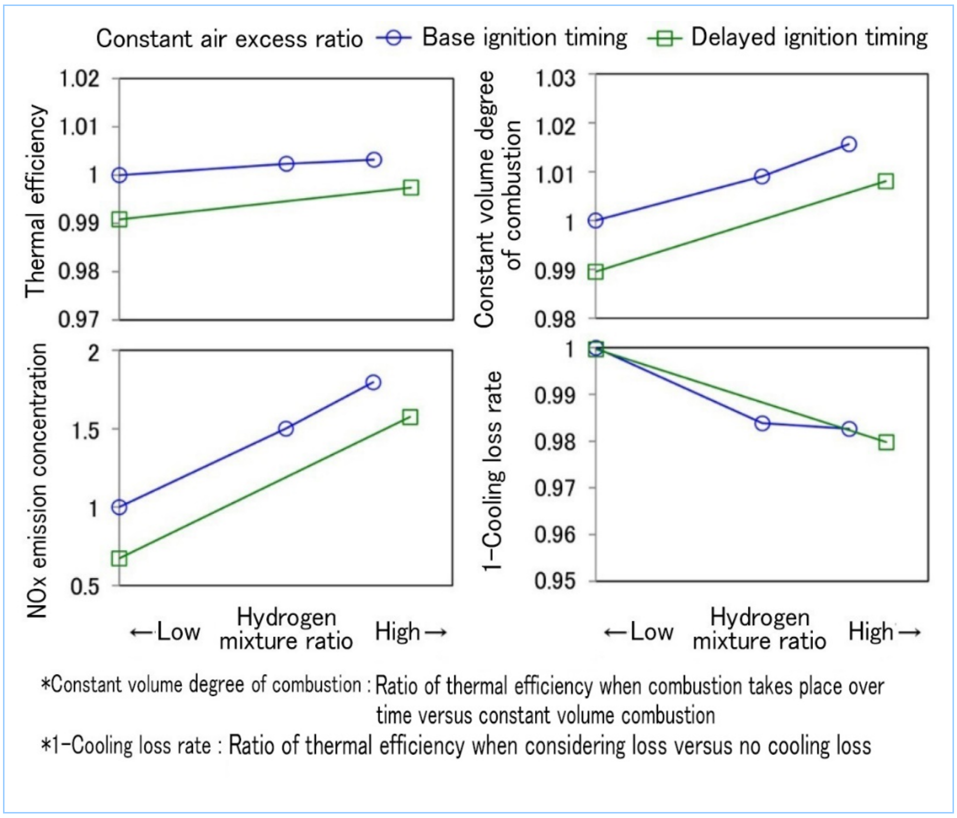


Figure 3 Various performances with respect to hydrogen mixture ratio

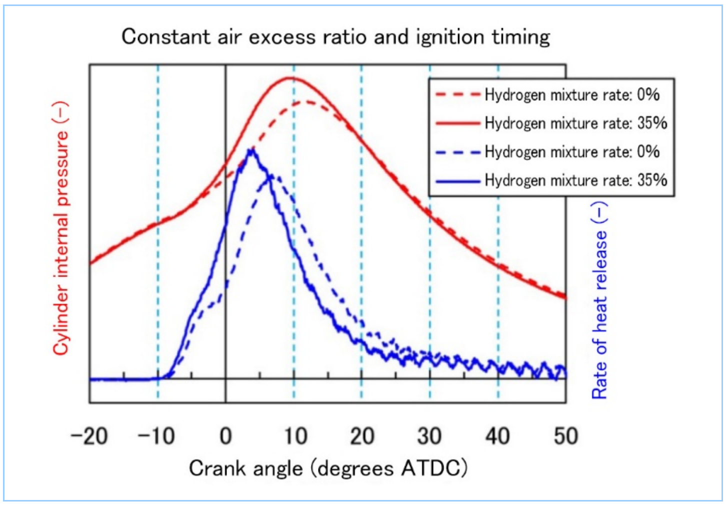


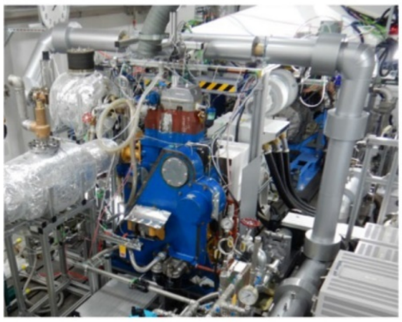
Figure 4 Comparison of internal cylinder pressures and rate of heat release

3. Development of 100% hydrogen combustion engine

We are developing hydrogen combustion engines fueled by 100% hydrogen and emit no CO_2. Through joint research with National Institute of Advanced Industrial Science and Technology (AIST) Fukushima Renewable Energy Institute, we have demonstrated the conditions for stable and highly efficient combustion of hydrogen, which burns at a high rate, using a single cylinder testing engine [(8)]. In addition, we are designing the multi-cylinder engine by making full use of numerical simulation methods for related elemental technologies such as flow, combustion, and strength, which we have accumulated in our research and development activities.

3.1 Single cylinder testing engine

We are in the process of evaluation for determining appropriate specifications and combustion conditions of hydrogen engines, utilizing a single cylinder testing engine. **Figure 5** shows the main specifications and operating conditions of the single cylinder testing engine. As an example, **Figure 6** shows the effect of optimizing the air excess ratio λ in hydrogen combustion. Because hydrogen combusts very quickly, the ignition timing range is narrow with an air excess ratio λ equivalent to that for natural gas due to the limitation caused by knocking avoidance. However, by making the air excess ratio appropriately lean, the combustion range can be extended and thermal efficiency and brake mean effective pressure can be improved. Currently, we are using this single cylinder testing engine to verify the proper specifications of compression ratio, intake valve closing timing, etc.



		Hydrogen combustion single cylinder testing engine
Cylinder bore	mm	170
Stroke	mm	220
Rated rotation speed	min^{-1}	1 500
Number of cylinders	—	1
Rated output	kW	75
Brake mean effective pressure	MPa	1.2
Combustion system	—	Open chamber-type lean combustion
Ignition system	—	Spark ignition

Figure 5 Main specifications and operating conditions of hydrogen combustion single cylinder testing engine

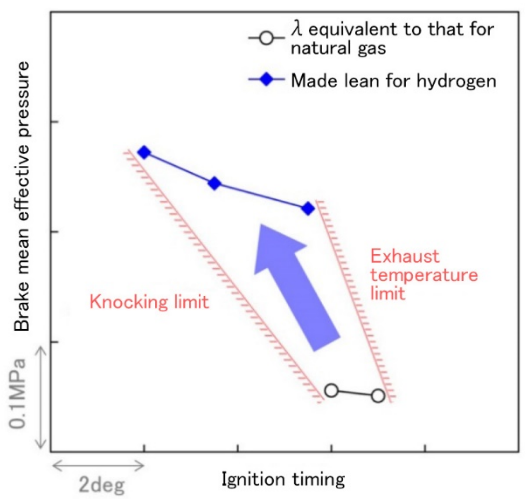
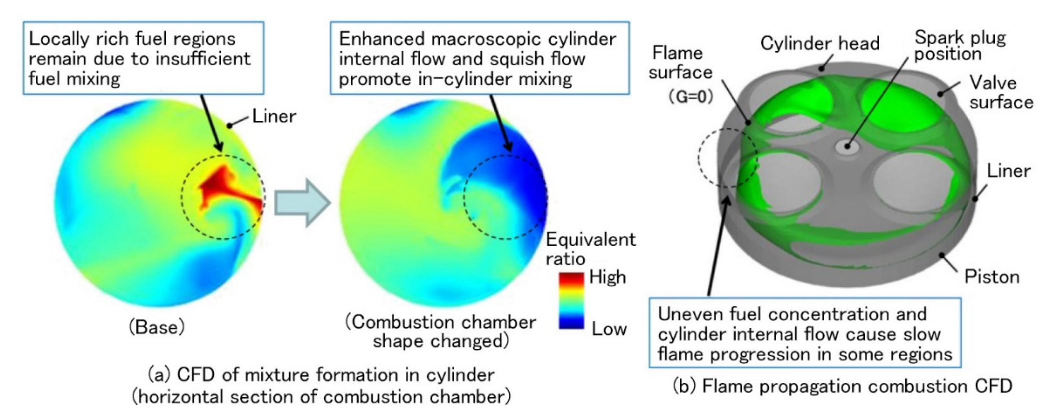


Figure 6 Example of result with single cylinder testing engine

3.2 Study through analysis related to multi-cylinder engine design

We use CFD (Computational Fluid Dynamics) analysis together with the single cylinder testing engine in selecting suitable combustion chamber specifications for the port injection and open chamber spark ignition system of 100% hydrogen combustion engines. First, **Figure 7**(a) shows the results of evaluating the fuel concentration uniformity of mixture in the cylinder for the adoption of port injection in the equivalent ratio contour diagram. This indicates that the macroscopic cylinder internal flow and squish effects are changed by optimizing the combustion chamber geometry to reduce locally rich fuel regions. Next, Figure 7(b) shows the result of evaluating the flame propagation in the cylinder under conditions where such mixture distribution exists. The presence of a region with extremely slow flame progression increases the risk of intense knocking in the region around it. By optimizing combustion chamber specifications in consideration of these factors, we are working to further improve the thermal efficiency and maximum power output.



Analysis code	CONVERGE
Combustion model	G equation + Detailed chemical reaction

Figure 7 Example of CFD analysis of mixture formation in cylinder and flame propagation combustion

3.3 Design of a multi-cylinder engine

As with the hydrogen/natural gas mixed combustion engine described in chapter 2, we are developing 100% hydrogen combustion engines based on our GSR lean burn gas engine series that have been marketed (**Figure 8**). In the case of hydrogen combustion, the combustion rate is even faster than that in hydrogen/natural gas mixed combustion, and the risk of abnormal combustion such as backfiring, pre-ignition, and knocking is higher. Therefore, there are issues of stabilizing combustion and reducing the risk of abnormal combustion. The following sections are describing technologies to address these issues.

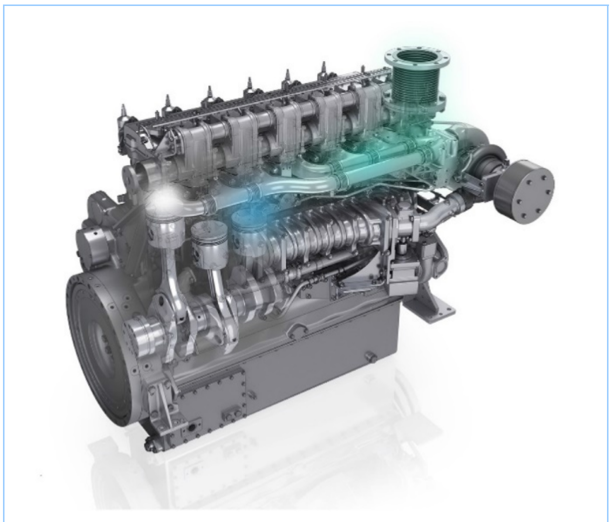


Figure 8 Hydrogen combustion engine

(1) Combustion stabilizing

To suppress the high combustion rate in 100% hydrogen combustion, the conventional pre-chamber spark ignition system used in the GSR series was changed to a open chamber spark ignition system (**Figure 9**). In addition, the compression ratio, intake valve closing timing, air excess ratio, and other factors were reviewed through the verification using the single cylinder testing engine described in section 3.1 to optimize the combustion rate and stabilize combustion.

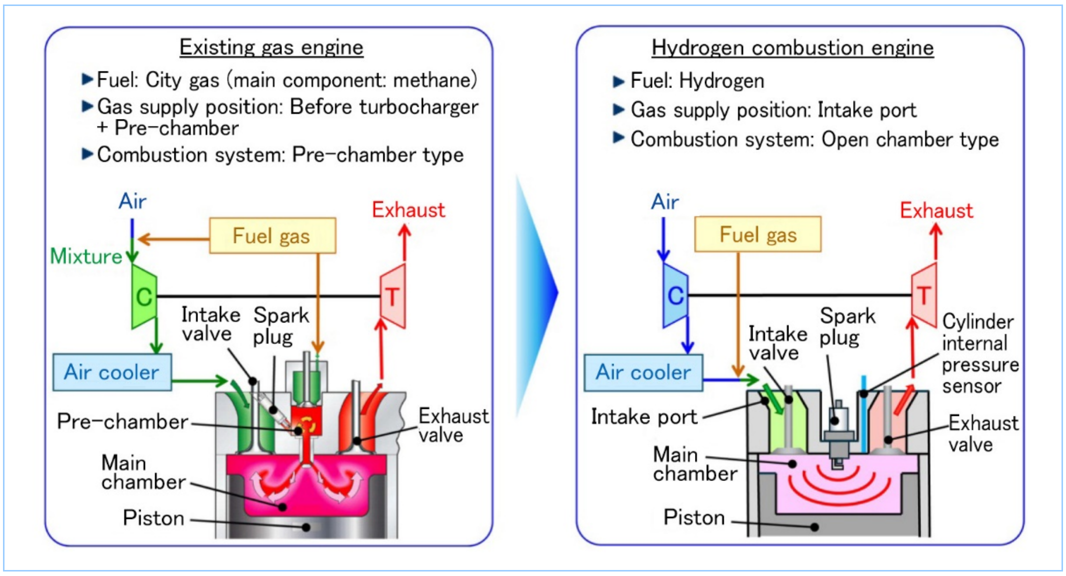


Figure 9 Air and fuel supply system (hydrogen combustion engine)

(2) Abnormal combustion risk avoidance

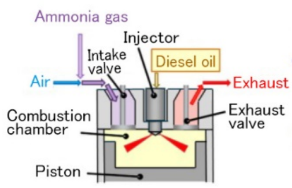
The 100% hydrogen combustion engine is equipped with additional cylinder internal pressure sensors compared to the conventional GSR series (Figure 9). The cylinder internal pressure sensors quickly detect abnormal combustion such as pre-ignition and knocking and stop the fuel supply to avoid the risk of engine damage due to abnormal combustion. In addition, for the hydrogen combustion engine, the conventional method of feeding fuel upstream of the turbocharger and supplying premixture through the turbocharger, which is used in the GSR series, is changed to a method of supplying fuel from the intake port of each cylinder (port injection method). By applying this method, the area where premixture exists in the intake system is limited to a minimum, and the risk of engine damage in the event of backfires can be reduced. We are proceeding with the design of multi-cylinder engine that addresses the issues as described above, and have a plan to begin verification tests on the performance and reliability using the multi-cylinder engine from fiscal 2023 onward.

4. Development of ammonia/diesel oil mixed combustion engine

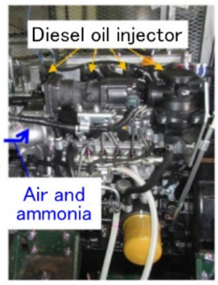
We are developing engines that can use ammonia, which is attracting attention as one of the new fuels for achieving carbon neutrality. Since ammonia can be produced from hydrogen, and can be liquefied easily by pressurizing and the volume is reduced, it is expected to be applied to marine engines, etc., where the fuel tank capacity is limited. The following sections describe the results of a test using our small engine to verify the greenhouse gas emission reducing effect.

4.1 Issues with ammonia combustion

Figure 10(a) shows the fuel supply system to the combustion chamber. Based on a conventional diesel oil fueled engine, this system has a configuration that supplies ammonia gas to the intake system so that the ratio of diesel oil and ammonia can be adjusted as desired according to operating conditions. The base engine is a small four-cylinder diesel engine equipped with a common-rail injection system that allows the injection amount and timing of diesel oil to be set freely, as shown in Figure 10(b) and Figure 10(c). There are issues with ammonia combustion: more unburnt combustible content is emitted because ammonia is more difficult to ignite than hydrogen or natural gas and has a lower combustion rate; nitrous oxide (N_2O), which has a greenhouse effect about 300 times greater than carbon dioxide, is produced by thermal decomposition of ammonia; and nitrogen oxide (NOx) is abundantly generated. As a result of predicting the gas mixture distribution in the combustion chamber by combustion simulation (**Figure 11**), it was found that a large amount of unburnt ammonia is retained at the edges, so promoting combustion in the area where the diesel oil flame cannot reach is an issue.



(a) Schematic view of fuel supply system



(b) Appearance of test engine

		D04EG
Cylinder bore	mm	94
Stroke	mm	120
Test rotation speed	min^{-1}	1 500
Number of cylinders	—	4
Test power output	kW	58
Brake mean effective pressure	MPa	1.39
Combustion system	—	Diesel diffusion combustion Ammonia premixed combustion

(c) Test engine specifications

Figure 10 Overview of ammonia/diesel oil mixed combustion engine

Analysis conditions

Analysis code	ANSYS FORTE
Combustion model	G equation + Detailed chemical reaction model

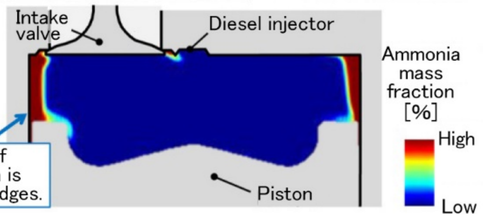


Figure 11 Ammonia combustion simulation result

4.2 Test result of ammonia/diesel oil mixed combustion

Figure 12 shows an example result of ammonia/diesel oil mixed combustion test using an actual engine. As a result of reducing the air excess ratio λ aiming to increase the combustion rate to promote the combustion of ammonia, the unburnt ammonia concentration in the exhaust decreased as shown in Figure 12(a). Also the N_2O concentration decreased, which can be attributed to the reduction in the amount of unburnt ammonia, one of the N_2O generation factors, as mentioned above, and to the increased temperature in the combustion chamber as a result of the decrease in λ, promoting consumption of N_2O. Furthermore, the accelerated combustion of ammonia enabled stable combustion even with a higher ammonia mixed combustion rate (ratio of the heat quantity of ammonia to that of the entire fuel) (Figure 12(b)), increasing the mixed combustion rate from the initial setting of 75% to 94%. Figure 12(c) shows the change in the greenhouse gas emission rate. The increase in ammonia mixed combustion rate and the reduction of N_2O resulted in an 82% reduction in greenhouse gas (GHG) emissions compared to the diesel oil combustion.

The negative effects of the decrease in λ include increased NOx and heat load on the combustion chamber and exhaust system components. We will continue to find appropriate settings through simulations and engine tests and accelerate the development of ammonia engines that contribute to achieving carbon neutrality.

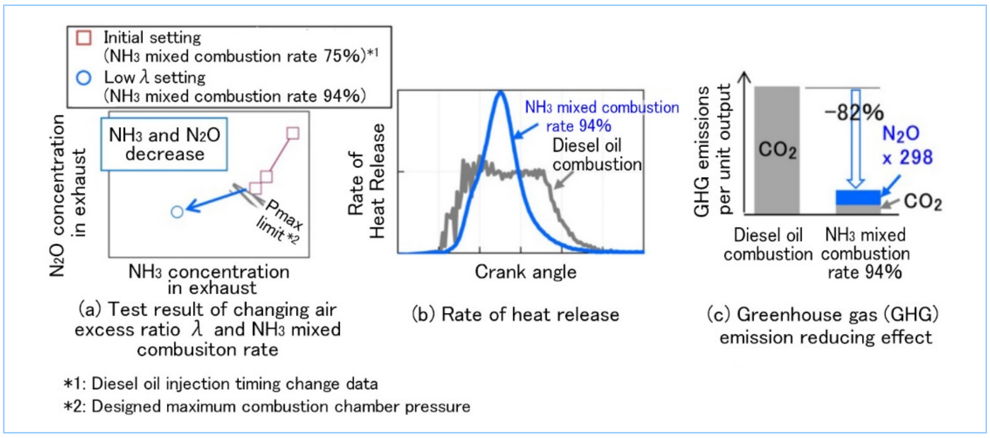


Figure 12 Test result of ammonia/diesel oil mixed combustion

5. Conclusion

We are currently conducting research and development of hydrogen/natural gas mixed combustion engines, 100% hydrogen combustion engines, and ammonia/diesel oil mixed combustion engines for use in distributed power sources and marine main/auxiliary engines, with a view to the low-carbon and carbon-neutral society that is expected to be realized in the future. Among them, the hydrogen/natural gas mixed combustion engines are now in the final stage of commercialization with the aim of improving the environmental burden and increasing customer value by bringing them to market at an early date. In addition, we will contribute to MISSION NET ZERO, in which MHI Group aims to achieve carbon neutrality by 2040, and to the realization of a sustainable society, through the timely development and commercialization of hydrogen combustion engines and ammonia combustion engines in response to the status of hydrogen and ammonia supply infrastructure, their penetration into the fuel market, and the needs of society and customers.

References

1. Masayuki Tanaka et al., Demonstration Testing of Triple-Hybrid Power Generation System toward Era of Distributed Power Sources- Development of “EBLOX” and “COORDY”, Mitsubishi Heavy Industries Technical Review Vol. 56 No. 2 (July 2019)
2. Mitsubishi Heavy Industries Co., Ltd. Press release (2021), https://www.mhi.com/jp/news/210623.html
3. Mitsubishi Heavy Industries Co., Ltd. Press release (2022), https://www.mhi.com/jp/news/22032201.html
4. Kohei Higaki et al., MHI Group's Recent CO_2 Capture Technology for Carbon Neutral Society, Mitsubishi Heavy Industries Technical Review Vol. 59 No. 2 (June 2022)
5. Mitsubishi Heavy Industries Co., Ltd. Press release (2022), https://www.mhi.com/jp/news/220602.html
6. New Engine Products for a Decarbonized Society, Mitsubishi Heavy Industries Technical Review Vol. 58 No. 2 (June 2021)
7. Toho Gas Co. Ltd., Mitsubishi Heavy Industries Co., Ltd. Press release (2021), https://www.mhi.com/jp/news/21082601.html
8. Mitsubishi Heavy Industries Co., Ltd. Press release (2021), https://www.mhi.com/jp/news/210121.html