CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

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Effects of hydrogen co-firing on the performance of the Mitsubishi KU30GSI gas engine

Fuels - Alternative & New Fuels

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ABSTRACT

The global movement towards achieving a low-carbon or decarbonized society is accelerating. Effective use of energy contributes to global low-carbon and decarbonization efforts to address climate change issues.

A gas engine cogeneration system (CHP), which can supply both heat and power electricity, is superior in energy saving. Mitsubishi Heavy Industries Engine & Turbocharger Co., Ltd. (MHIET), a member of Mitsubishi Heavy Industries (MHI) group, offers a lineup of gas engines covering the range from 315 kW to 5,750 kW per unit and can therefore provide products for use as small-scale distributed power sources, cogeneration systems for facilities, factories and such, or power generation for utility supplies using multiple units.

In order to utilize hydrogen for realizing a low-carbon or decarbonized society, it would be necessary to promote the development of a large-scale hydrogen supply chain and the creation of demand in an integrated manner. In the use of hydrogen in the power generation sector, such as gas engines for power generation, hydrogen co-firing which does not require major changes such as engine replacement is considered to support power generation demand during the transition to a carbon-neutral society.

Under such circumstances, as a part of the progress of hydrogen utilization in gas engines for power generation, hydrogen co-firing tests were carried out in a single cylinder test facility of 18cyl KU30GSI gas engine which output is 5,750kW.

This paper describes the test results and its examinations. In the test, operation condition was found which can realize stable combustion up to 50vol% hydrogen co-firing with Japanese city gas 13A at rated power. Based on the results, the effect of hydrogen co-firing on engine performance as a cogeneration system is estimated. In addition, the pure hydrogen combustion test was also carried out, and the example of the pre-ignition combustion behavior observed in the high load is also introduced.

1 INTRODUCTION

The global movement towards achieving a low-carbon or decarbonized society is accelerating. Effective use of energy contributes to global low-carbon and decarbonization efforts to address climate change issues.

In order to utilize hydrogen for realizing a low-carbon or decarbonized society, it would be necessary to promote the development of a large-scale hydrogen supply chain and the creation of demand in an integrated manner [1]. In the power generation sector, the use of hydrogen in gas engines [5] through co-firing — without major modification like engine replacement — is considered a way to support power generation demand during the transition to a carbon-neutral society.

Generally, hydrogen supply chains are developed region by region. This indicates that relatively small-scale power generation systems are realistic option for hydrogen power generation. Considering this background, hydrogen co-fired power generation using a gas engine CHP (Combined Heat and Power plant) with high power generation efficiency would be one of the practical solutions.

One of the technical challenges in using hydrogen as a fuel for power generation gas engines is the combustion characteristics of hydrogen. Compared to natural gas, hydrogen is broader in the flammability range, faster in the burning velocity, and smaller in the minimum ignition energy. This means that abnormal combustion, such as knocking, pre-ignition, and backfires, are more likely to occur when hydrogen is used as a fuel [2]. In addition, for efficient energy utilization, the exhaust gas temperature should be high level to minimize the reduction in exhaust gas-based steam generation while keeping power output and power generation efficiency as high as possible during hydrogen co-firing.

This paper describes the results of an investigation into the effects of a hydrogen-natural gas mixture. The investigation was conducted using a single-cylinder test engine of a 5,750 kW medium-speed power generation gas engine. The focus of the study was on combustion characteristics and engine performance.

In addition, pure hydrogen test was also performed, and case examples of combustion with continuous and stable pre-ignition appeared in pure hydrogen operation are described.

2 GAS ENGINE MODELS OF MHIET

Gas engine CHP, which can supply both heat and power electricity, is superior in energy saving.

Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET), a member of Mitsubishi Heavy Industries (MHI) group, has been developing gas engines since the early 1990s and has delivered them to many customers as distributed CHP. MHIET’s gas engine offerings include products for small-scale distributed power generation, CHP for facilities and factories, and commercial power generation. These include the GSR series, a high-speed gas engine with a power output range of 315 to 1,500 kW. The GNB type enhances the power generation efficiency of GSR and can output 2,000 kW in a compact design. Additionally, the KU30GSI series is a medium-speed gas engine that covers a range of 3,650 to 5,750 kW. Figure 1 presents photographs of external view, while Table 1 outlines the major specifications of MHIET gas engines.

Figure 1. External view of MHIET gas engines

Table.1 Lineup of MHIET gas engines

Engine Type			GSR Series							GNB	KU30GSI Series			
			GS6R2		GS12R	GS16R		GS16R2		G16NB	12KU 30GSI	14KU 30GSI	16KU 30GSI	18KU 30GSI
Bore / Stroke		mm	170 / 220		170 / 180			170 / 220			300 / 380			
50Hz	Output	kW	315	500	700	930	-	1000	1500	2000	3800	4450	5100	5750
	Speed	min^{-1}	1000	1500			-	1000	1500		750			
60Hz	Output	kW	380	450	610	815	850	1000	1200	-	3650	4250	4900	5500
	Speed	min^{-1}	1200							-	720			

The hydrogen co-firing test described in this paper was conducted using a single-cylinder test engine of KU30GSI. This engine has a maximum output of 5,750 kW in its 18-cylinder configuration. it achieved the world's highest level of total efficiency in both power and steam generation by enhancing power generation efficiency and increasing exhaust gas temperature. The KU30GSI demonstrates high start-up performance and load-following capability, making it suitable for private power generation facilities in factories, commercial power generation, and various other applications.

The KU30GSI uses a spark plug ignition system, and approximately 80% of parts used are the same as other models: previous model of KU30GA gas engine with micro pilot ignition, and the KU30A diesel engine. The design allows for retrofitting to the latest KU30GSI while making maximum use of components of the existing KU30A and KU30GA. This makes the KU30GSI effective for extending the life of field operating engines. The hydrogen co-firing discussed in this paper can also be implemented by retrofitting existing engines, contributing to a reduction in the CO_2 emission coefficient with minimal capital investment.

In the KU30GSI series, "cogeneration system (CGS) with all steam recovery" has been established, in which the outlet temperature of jacket cooling water (JCW) is raised to 120°C to provide a stable source of heat for producing steam [6]. The produced steam is then utilized together with steam generated from other components, such as the exhaust gas boiler. The CGS with all steam recovery gas engine started field operation in 2018. This system can significantly improve heat-to-power ratio in comparison to the conventional gas engines. Currently, there are three engines in operation, and their total operating time has exceeded 65,000 hours without any major issues affecting engine reliability or operability.

Implementing hydrogen co-firing in this all-steam-recovery configuration can further reduce the CO_2 emission coefficient for combined power generation and steam production. Results from hydrogen co-firing tests with this all-steam-recovery configuration are also described in this paper.

3 TEST FACILITIES

3.1 Engine

Table 2 presents the specifications of the test engine. The test was conducted using a single-cylinder version of the KU30GSI, an 18-cylinder gas engine with a generator output of 5,750 kW.

Table 2. Specifications of the test engine

Number of cylinders	1
bore / stroke [mm]	300 / 380
Displacement [L]	26.9
engine speed [min^{-1}]	750
Combustion system	Prechamber lean-burn Spark Ignition

This engine is a spark-ignition gas engine with a prechamber. The spark plug ignites the air-fuel mixture in the prechamber, generating torch jet that burns the lean air-fuel mixture in the main chamber. The fuel gas supply to the main chamber and the prechamber is controlled by the gas supply pressure and the opening duration of the gas supply solenoid valve. The fuel gas is supplied to the main chamber through the intake port, and to the prechamber directly.

3.2 Test Facilities

Figure 2 shows a configuration diagram of the test facility. The intake air is supplied by a compressor operated by external power, and the exhaust pressure is regulated by a flap valve in the exhaust pipe. The intake air temperature can be controlled using a cooler installed after the compressor.

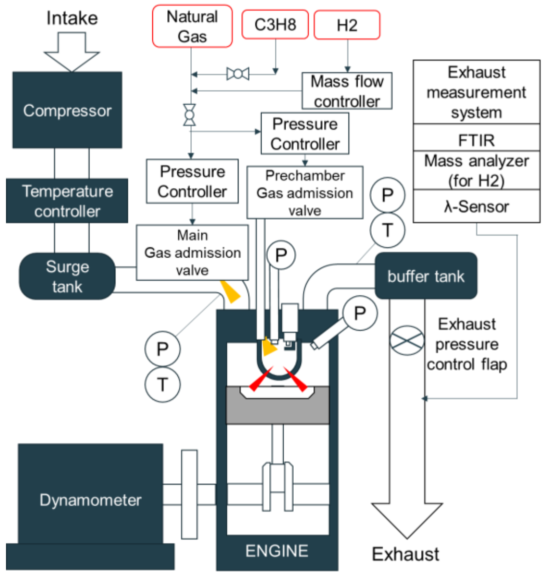

Figure 2. Diagram of test facilities

In this test, an equivalent gas to Japanese city gas 13A (Table 3), which is a mixture of natural gas and propane, is used as the base fuel. The hydrogen co-firing test is conducted by mixing hydrogen with the city gas 13A-equivalent gas. Based on the measured mass flow rate of the fuel gas, the volumetric percentage of hydrogen is calculated.

Table 3. Typical composition of Japanese city gas 13A

		City Gas 13A
Methane	%	89.6
Ethane	%	5.6
Propane	%	3.4
Butane	%	1.4
Methane Number	-	68.8
LHV	MJ / Nm3	40.8

Exhaust gas components such as NOx and CO_2 are measured using an exhaust gas analyzer. Additionally, thermocouples are installed in the cylinder head and cylinder liner to measure the temperature at multiple points in the combustion chamber.

4 HYDROGEN CO-FIRING TEST

4.1 Conventional type test

4.1.1 Test Conditions

Table 4 shows the specifications of the tested engine. The test was conducted based on the latest gas engine specifications. additionally, two cases were examined in which the expansion ratios were lowered to suppress abnormal combustion during hydrogen co-firing. The expansion ratio refers to the ratio of the cylinder volume when the piston is at the bottom dead center position to the volume when it is at the top dead center position. In Case 2, the actual compression ratio - the ratio of the cylinder volume when the intake valve closes to that when the piston is at the top dead center position - is made equal to that of Case 1 by delaying the closing timing of the air intake valve.

Table 4. Tested engine spec.

		Base	Case1	Case2
Expansion Ratio	–	Base	-0.5	-1.5
IVC	degBTDC	Base	Base	-14
Rated IMEP	MPa	2.15	2.15	2.15

Note : Values are expressed in the difference of the base specification.

Table 5 shows the test conditions. The fuel used is a mixture of city gas 13A-equivalent gas and 30-50 vol% hydrogen. The tests are conducted with the excess air ratio, ignition timing, and other parameters adjusted to the stable operation range for each specification and fuel type.

Table 5. Test Conditions (Parameters)

Items	Description
Base Fuel	City Gas 13A
Volume Fraction of Hydrogen	0%, 30%, 40%, 50%
Excess Air Ratio	Base to +20%
JCW Outlet Temperature	92°C

4.1.2 Test results

4.1.2.1 Relation between pre-ignition and expansion ratio

Compared to city gas 13A, hydrogen has a wider flammable range and a lower minimum ignition energy, making pre-ignition more likely to occur. Since the occurrence of pre-ignition leads to an increase in firing pressure and combustion chamber temperature, we first determined the engine specifications that would suppress pre-ignition. Figure 3 shows an example of cylinder pressure during the occurrence of pre-ignition. In Figure 3, the solid line represents the pressure of normal combustion, while the dashed line represents the pressure of pre-ignition. When combustion in the prechamber starts, the pressure in the prechamber increases relative to the pressure in the main chamber. Normally, this occurs after the ignition timing. In contrast, during pre-ignition, the prechamber pressure begins to increase before the ignition timing, resulting in a higher maximum pressure of the main chamber.

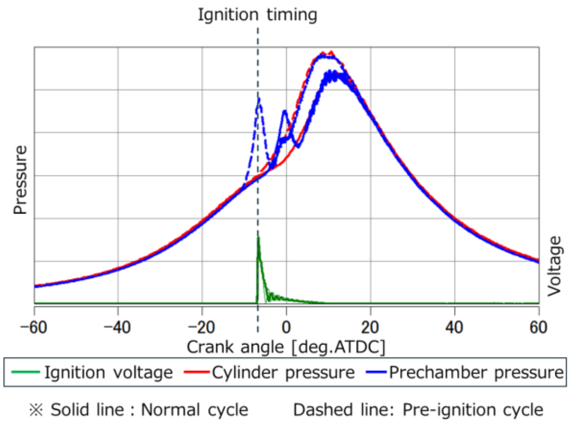

Figure 3. Cylinder pressure of pre-ignition cycle

Figure 4 shows the occurrence rate of pre-ignition during rated IMEP operation for each specification. In the case of hydrogen co-firing at a mixture ratio of 50 vol%, the base specification exhibited pre-ignition even with an increased excess air ratio. In contrast, Case 1, which has a lower expansion ratio, demonstrated improvement. Case 2, with an even lower expansion ratio, exhibited no pre-ignition even at a relatively low excess air ratio.

These results indicate that the expansion ratio must be reduced to operate at the rated IMEP without pre-ignition. The following paragraphs describe the performance characteristics of hydrogen co-firing based on the test results from Case 2, which provides a sufficient margin against pre-ignition.

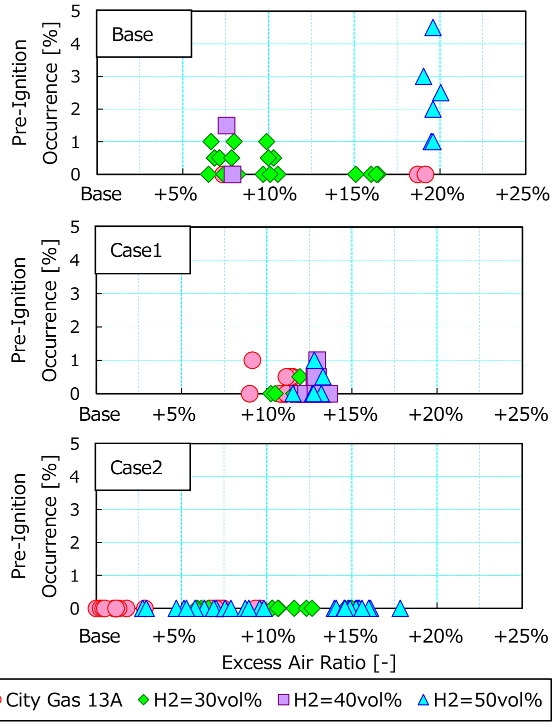

Figure 4. Pre-ignition occurrence in rated IMEP operation (IMEP=2.15MPa)

4.1.2.2 Engine Performance

Figure 5 and Figure 6 illustrate the typical performance during hydrogen co-firing at the IMEP in Case 2. For hydrogen co-firing, the excess air ratio (λ) is increased compared to that in the case of city gas 13A, which leads to an increase in the intake pressure. Therefore, the specifications of turbocharger need to be appropriately selected for practical use.

In the case of hydrogen co-firing at a hydrogen mixture ratio of 30 vol%, the peak firing pressure (PFP) and NOx levels in exhaust gas are equivalent to or lower than those observed during operation with city gas 13A. This is provided that λ is leaner by 5% or more and the ignition timing is retarded by approximately 2.0 degrees CA or more.

Similarly, at a hydrogen mixture ratio of 50 vol%, when λ was leaner by 10% or more and the ignition timing was retarded by approximately 4.0 degrees CA or more, the PFP and NOx levels in exhaust gas remain equivalent to or lower than those in operation with city gas 13A.

Thermal efficiencies during hydrogen co-firing are sometimes better and sometimes worse than those observed during operation with city gas 13A, depending on the operating conditions. The efficiencies remained the same or decreased by no more than 0.5 percentage points whenever the λ and ignition timing were within the range that resulted in PFP and NOx levels in the exhaust gas being equivalent to or lower than those during operation with city gas 13A. This suggests a combination of effects: improved combustibility from hydrogen co-firing, enhanced cycle efficiency due to higher λ, and reduced combustibility resulting from leaner fuel.

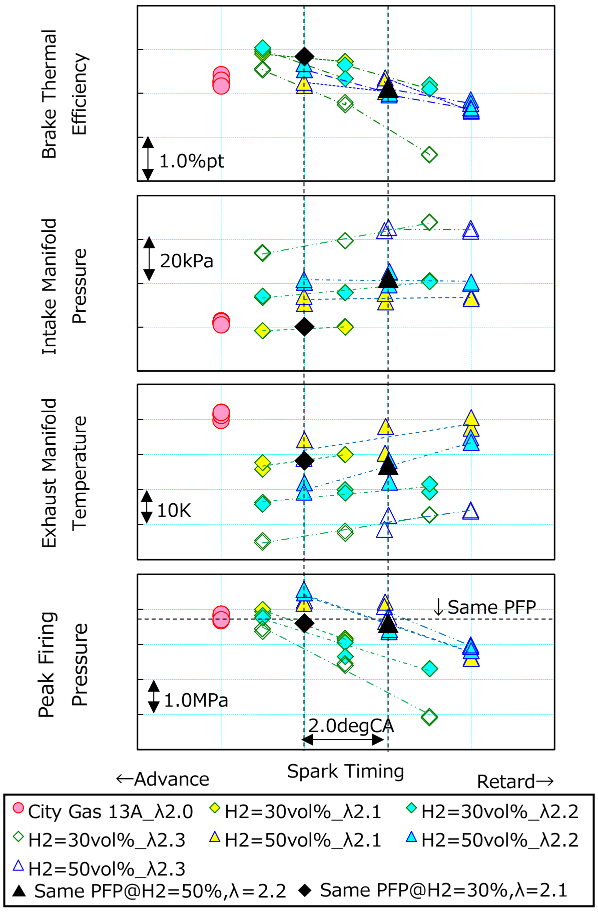

Figure 5. Test results of performance at rated IMEP operation (IMEP=2.15MPa)

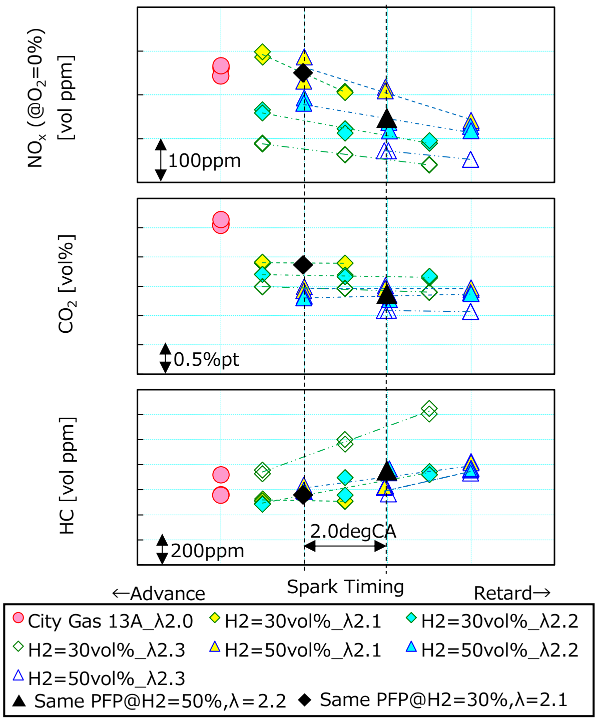

Figure 6. Test results of exhaust gas composition at rated IMEP operation (IMEP=2.15MPa)

The NOx emissions in the exhaust gas from hydrogen co-firing are equal to or lower than those observed during operation with city gas 13A. The HC emissions from hydrogen co-firing, except for the case of 15% leaner λ at a hydrogen mixture ratio of 30 vol%, tended to be equal to or lower than those from operation with city gas 13A. This reduction of NOx is attributed to the effects of increased λ and retarded ignition timing. The behavior of HC emission can be attributed to a combination of factors; lower hydrocarbon content in the fuel, improved combustibility from hydrogen co-firing, and reduced combustibility from operation at higher λ.

This result suggests that when the PFP is maintained at or below the level observed during operation with city gas 13A, setting appropriate λ and ignition timing will ensure that the decrease in thermal efficiency. This decrease during hydrogen co-firing, compared to that during operation with city gas 13A, will remain within 0.5 percentage points. Additionally, the NOx emissions and any unburned content in the exhaust gas from hydrogen co-firing will be kept equal to or lower than those from operation with city gas 13A.

4.1.2.3 Combustion Chamber Wall Temperature

During operation with city gas 13A and during hydrogen co-firing, the wall temperatures of the combustion chamber (cylinder head and cylinder liner) were also measured in the test.

Figure 7 shows the measurement points. Measurements were taken at five radial points on the cylinder head surface between the exhaust valves, where the temperatures are high, and at four circumferential points on the cylinder liner, corresponding to the position of the piston's top ring when the piston is at top dead center. Figure 8 presents the measurement results.

The cylinder head temperature values shown in this figure are relative to the reference measurement point, which is closest to the center during operation with city gas 13A. Similarly, the cylinder liner temperature values are relative to measurement point in direction A during city gas 13A operation. The comparison was conducted under conditions where the PFP and the cylinder head outlet exhaust gas temperature were the same for both operations: city gas 13A at the rated IMEP and hydrogen co-firing at the rated IMEP.

Even under conditions where the PFP and the exhaust gas temperature were the same, the combustion chamber wall temperature was higher during hydrogen co-firing than during operation with city gas 13A. The temperature difference between operation with city gas 13A and hydrogen co-firing at a hydrogen mixture ratio of 50 vol% was approximately 5°C at the cylinder head and about 10°C at the cylinder liner.

In general, the flame extinguishing distance of hydrogen is characteristically short. Therefore, it is believed that the amount of heat transferred from the flame to the combustion chamber wall increases due to a thinner temperature boundary layer on the wall [3]. The results of these temperature measurements indicate that the heat input from the combustion gas increased during hydrogen co-firing.

However, it was confirmed that the combustion chamber wall temperature during hydrogen co-firing under the operating conditions was lower than the maximum temperature allowed for each part in the actual engine. This is to the operation at higher excess air ratio.

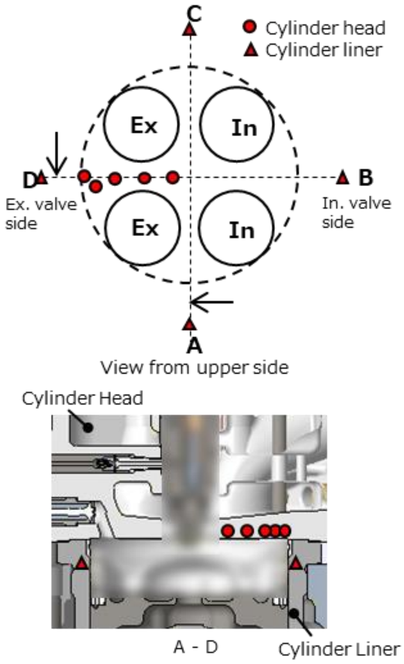

Figure 7. Temperature measurement position of cylinder head and cylinder liner

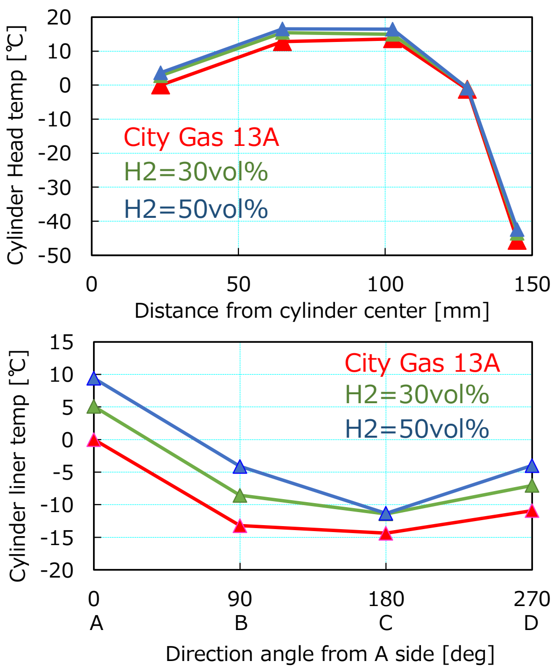

Figure 8. Temperature measurement results

4.1.2.4 Estimation of actual engine performance

Based on the test results, we estimated the thermal efficiency and exhaust gas temperature for hydrogen co-firing in an actual engine. The operating conditions for this estimation were set to the rated IMEP conditions defined in Case 2.

Figure 9 shows the estimation results. When the peak firing pressure is the same as that during operation with city gas 13A, the thermal efficiency decreases by only 0.5 percentage points or less, regardless of the hydrogen mixture ratio. As the hydrogen mixture ratio increases, and subsequently the excess air ratio increases, the exhaust gas temperature at the turbocharger outlet decreases. When the hydrogen mixture ratio reaches 50%, the exhaust gas temperature is expected to decrease by approximately 32 K compared to operation with city gas 13A.

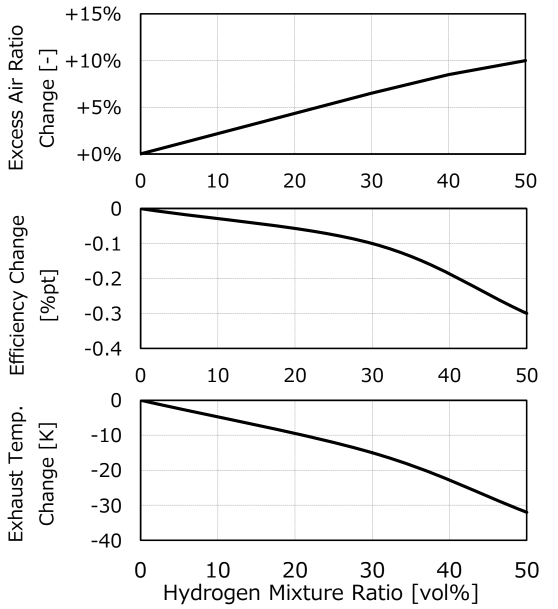

Figure 9. Prediction of engine performance with hydrogen mixture operation (on Case2 spec.)

Figure 10 presents the preliminary calculation results of CO_2 emission coefficients [6][7] when an actual engine is used as a CHP for power generation and steam generation using exhaust gas heat. The CO_2 emission coefficient for operation with city gas is 0.31 kg-CO_2/kWh. As a result of this test, this coefficient is expected to be reduced to 0.27 kg-CO_2/kWh for hydrogen co-firing at a hydrogen mixture ratio of 40 vol%. For hydrogen mixture ratio of 50 vol%, the coefficient is expected to be reduced to 0.26 kg-CO_2/kWh. The EU has established the EU Taxonomy, which systematically organizes world-first environmentally sustainable economic activities. The Taxonomy stipulates that the direct CO_2

emissions of gas-fired power generation projects permitted to be constructed by the end of 2030 must be less than 0.27 kg-CO_2/kWh [4]. These test results suggest that the power generation and steam utilization of the actual engine operating with hydrogen co-firing are expected to meet the CO_2 emission coefficient set in the EU Taxonomy.

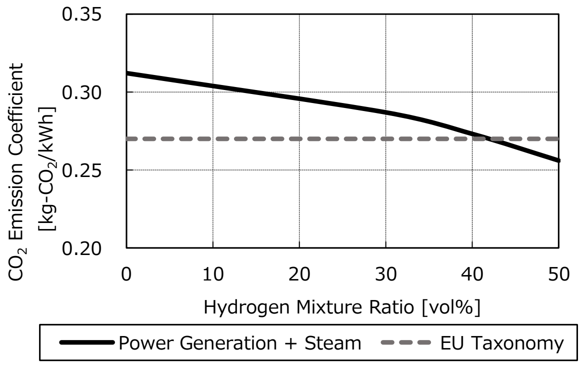

Figure 10. CO2 emission coefficient from power generation and steam

4.2 All-steam recovery type test

4.2.1 Test Conditions

Table 6 presents the conditions for the all-steam recovery type configuration test. Similar to the conventional type tests, the fuel used is a mixture of city gas 13A-equivalent gas and 30-50 vol% hydrogen. Each parameter, such as excess air ratio, ignition timing, is adjusted based on the results from conventional type tests.

Table 6. Test Conditions

Items	Description
Engine Spec.	Case 2 of Table 4
Base Fuel	City Gas 13A
Volume Fraction of Hydrogen	0%, 30%, 50%
Excess Air Ratio	Base to +10%
JCW Outlet Temperature	120°C

4.2.2 Test results

Figure 11 illustrates the test results during hydrogen co-firing at rated IMEP in the all-steam recovery type configuration operation. The engine specifications for the illustrated data correspond to Case 2 in Table 4. It is confirmed that stable operation with hydrogen co-firing of up to 50 vol% hydrogen in the all-steam recovery type configuration is possible. This is achieved by adjusting the excess air ratio and ignition timing at the IMEP of 2.15 MPa.

Thermal efficiencies during hydrogen co-firing with all-steam recovery type configuration were nearly the same level of those observed during operation with city gas 13A. This was achieved while maintaining PFP level equivalent to that of city gas 13A by adjusting the excess air ratio and ignition timing. Similar to conventional type, it is considered to be influenced by a combination of factors: improved combustibility from hydrogen co-firing, enhanced cycle efficiency and reduced combustibility due to higher λ, and increased combustibility resulting from higher cooling water temperature.

The NOx and HC emissions in the exhaust gas from hydrogen co-firing with the all-steam recovery type configuration are lower than those observed during operation with city gas 13A.

Based on these results, stable operation with hydrogen co-firing of up to 50 vol% hydrogen in the all-steam recovery type configuration is expected by optimizing operating conditions, without changing major engine components. The performance and CO_2 emission coefficients estimations for the actual engine are still under investigation.

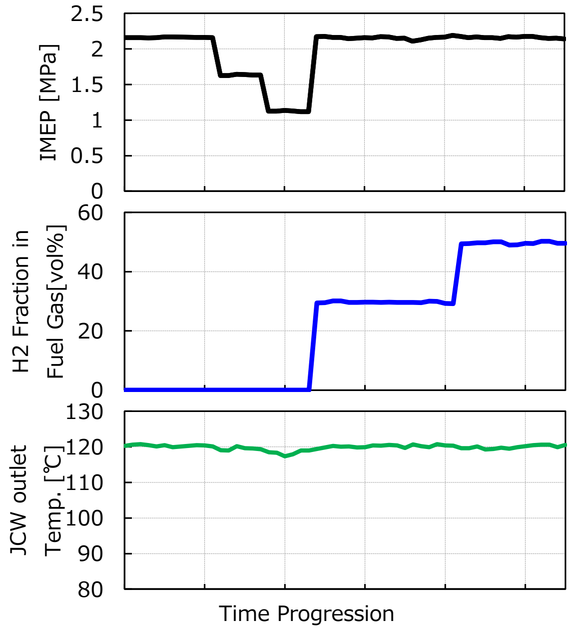

Figure 11. Test results of All-steam recovery configuration

5 PURE HYDROGEN TEST

This section describes the characteristic phenomena observed during the pure hydrogen test. Figure 12 illustrates the relationship between ignition timing and the 5% Mass Burnt Position (5% MBP), defined as the crank angle at which the burning ratio reaches 5%, serving as an index of the start of combustion. When IMEP is equal to or greater than 1.5 MPa, the 5% MBP remains nearly constant at around -5 degrees ATDC, even when the ignition timing is retarded up to the TDC. The cycle fluctuation of the 5% MBP is small, and pre-ignition occurred stably and continuously, similar to compressive self-ignition combustion.

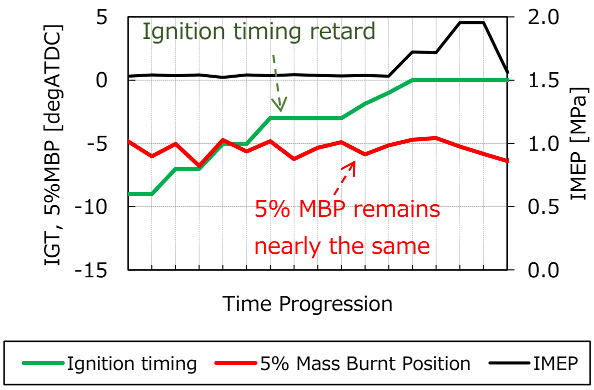

Figure 12. Ignition timing and 5% MBP in pure hydrogen test at IMEP of 1.5 to 1.95 MPa

Figure 13 shows an example of cylinder pressure at the IMEP of 1.95 MPa. In this example, stable pre-ignition occurred, but the high-frequency pressure oscillations typically associated with knocking were not observed.

In addition, an increase in prechamber pressure before that of the main chamber − a characteristic of prechamber-type gas engines − was not observed during pre-ignition. The waveforms of the prechamber pressure and main chamber pressure were nearly identical, suggesting that pre-ignition occurred in the main chamber.

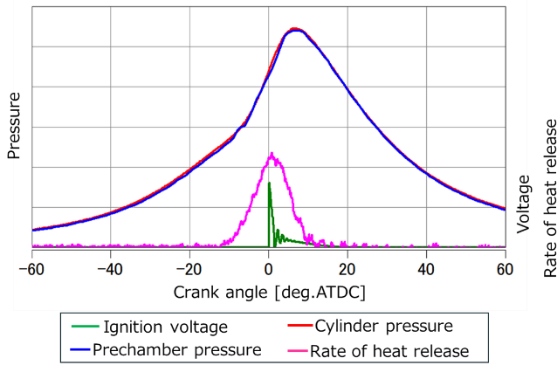

Figure 13. Cylinder pressure of pure hydrogen test @ IMEP=1.95 MPa

Continuous and stable pre-ignition occurred when the IMEP was equal to or greater than 1.5 MPa. However, combustion stability changed significantly with operating time when the ignition timing was at the TDC and the IMEP was reduced to 1.3 MPa. Figures 14 and 15 illustrate the time course of the cylinder pressure waveforms. Although the fuel gas supply rates in the cases shown in Figures 14 and 15 are the same, the IMEP decreased as combustion stability worsened. As the combustion chamber temperature decreased over time, there may be a correlation between the combustion chamber temperature and pre-ignition. We will continue to investigate this phenomenon.

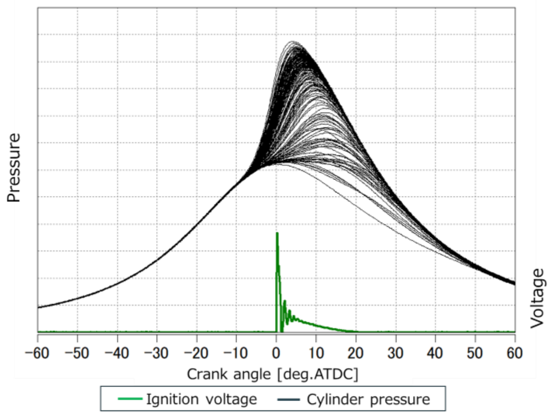

Figure 14. Cylinder pressure fluctuation of pure hydrogen test @ IMEP=1.3MPa just after IMEP reduction from 1.5 to 1.3 MPa

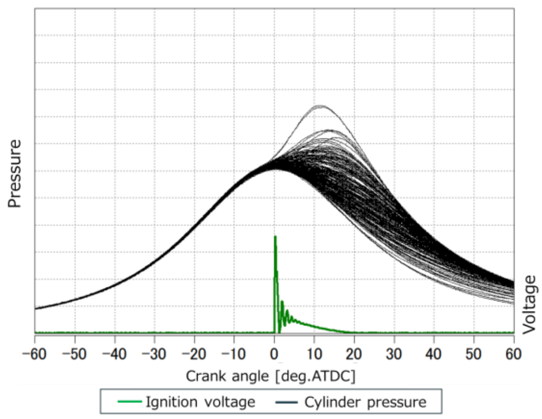

Figure 15. Cylinder pressure fluctuation of pure hydrogen test @ IMEP=1.1MPa few minutes after Figure 13 (all settings are identical to Figure 13)

6 CONCLUSIONS

Using a single-cylinder test engine of the KU30GSI gas engine, which operates with a mixture of city gas 13A equivalent and hydrogen, the effects of hydrogen co-firing on the engine performance were investigated. Additionally, pure hydrogen tests were conducted to identify potential issues. The findings of these tests are as follows.

(1) To achieve stable operation with hydrogen co-firing, reduction of the expansion ratio is effective in suppressing pre-ignition while maintaining the power output.

(2) To maintain peak firing pressure and NOx levels in the exhaust gas equivalent to or lower than those during operation with city gas 13A, it is necessary to increase the excess air ratio (λ) and retard the ignition timing. In hydrogen co-firing, NOx levels decrease due to the higher λ. However, hydrocarbon (HC) emissions can either increase or decrease depending on the operating conditions, influenced by both the higher λ and the reduction of carbon content in the fuel.

(3) The cylinder head and cylinder liner temperatures during hydrogen co-firing at hydrogen mixture ratio of up to 50 vol% increased by a maximum of 5 to 10°C for each component compared to operation with city gas 13A under the same conditions of peak firing pressure and exhaust gas temperature. It was confirmed that the combustion chamber temperature during hydrogen co-firing under the operating conditions was lower than the maximum temperature allowed for each component in the actual engine.

(4) Based on these test results, the CO_2 emission coefficient of utilizing the electricity and steam generated by the power generation gas engine is expected to be reduced to 0.27 kg-CO_2/kWh for hydrogen co-firing at a hydrogen mixture ratio of 40 vol%. For hydrogen co-firing at a hydrogen mixture ratio of 50 vol%, the CO_2 emission coefficient is expected to be reduced to 0.26 kg-CO_2/kWh.

(5) In the all-steam recovery type configuration, stable operation with hydrogen co-firing of up to 50 vol% hydrogen is expected by optimizing operating conditions.

(6) In pure hydrogen test, stable and continuous pre-ignition occurred earlier than the ignition timing when the IMEP was 1.5 MPa or higher.

Future Prospects

Based on these test results, the specifications for achieving stable combustion of the KU30GSI at hydrogen co-firing rates of up to 50 vol% have been clarified. In the future, we will proceed with the design of the engine main unit, plant facilities, and control specifications for hydrogen co-firing, aiming for commercialization.

Regarding pure hydrogen operation, we are developing a 6-cylinder, 500-kW-class pure hydrogen engine and incorporating it into a power generation system. We have constructed a hydrogen engine power generation system and hydrogen supply equipment at our Sagamihara Plant and we began demonstration tests in 2024.

For the operation of the KU30GSI gas engine on pure hydrogen, we plan to determine engine specifications that are capable of suppressing abnormal combustion and to evaluate its performance based on the single-cylinder test results.

MHIET's product line includes gas engine CHP with a wide range of outputs, which are energy-efficient distributed energy systems. These CHP have the potential for pure hydrogen operation as well as synthetic methane operation and can accommodate hydrogen co-firing during the transition period. We believe that gas engine CHP will play a crucial role in meeting energy demands and achieving a carbon-neutral society, including throughout the transition period.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

5% MBP: 5% Mass Burnt Position

ATDC: After Top Dead Center

BTDC: Before Top Dead Center

CGS: Cogeneration system

CHP: Combined Heat and Power plants

IMEP: Indicated Mean Effective Pressure

IVC: Timing of Intake Valve Closing

JCW: Jacket Cooling Water

LHV: Lower Heating Value

PFP: Peak Firing Pressure

ROHR: Rate of Heat Release

MHI: Mitsubishi Heavy Industries, Ltd.

MHIET: Mitsubishi Heavy Industries Engine & Turbocharger, Ltd.

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