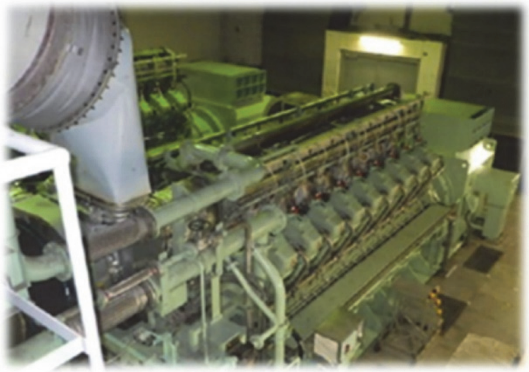
CO_2 Reduction and Hydrogen Utilization Technology for Power Generation Gas Engine KU30GSI



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Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (MHIET) provides gas engine cogeneration systems that can be used for various applications from small-scale distributed power sources to commercial power generation. The gas engine cogeneration system (CGS) with all steam recovery, which uses cooling water as a heat source for steam recovery by raising its temperature, has been in operation for a long time as a system that reduces the CO_2 emission factor of gas engine power generation facilities. In addition, MHIET conducted hydrogen co-firing combustion tests on a single-cylinder test engine of KU30GSI to verify the actual performance at up to 50 vol% hydrogen co-firing rate and the effect of CO_2 emission factor reduction. In the future, we will commercialize a hydrogen co-firing gas engine using the obtained hydrogen utilization technology.

1. Introduction

The 7th Strategic Energy Plan was formulated by the Japanese government in February 2025 in light of the global trend toward decarbonization and the growing tension in international energy security. The Plan calls for thorough energy conservation and promotion of the use of non-fossil fuels.

Natural gas, which emits the lowest amount of CO_2 among fossil fuels, has been increasingly used as an alternative energy source to petroleum and is considered an important fuel in the transition period to non-fossil fuels such as hydrogen. Gas engines use various gases as fuel, including natural gas and Japanese city gas, and can also use hydrogen to generate electricity. Due to the earthquake resistance of gas pipelines, gas engine power generation has the resilience to supply energy and is expected as a system that can stably generate power even in the event of a large-scale disaster.

Against such a background, gas engines are used in a wide range of power outputs for a variety of applications including cogeneration systems (combined heat and power plants, hereinafter referred to as CHP) because of their advantages of high start-up performance, load-following capability, and flexibility in waste heat recovery. Gas engine maintains excellent power generation efficiency and achieves an overall efficiency of more than 80% with efficient waste heat recovery due to high exhaust gas temperature and is considered one of the best choices for energy solutions.

Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (hereinafter referred to as MHIET) has an engine line that includes GSR, a 315 to 1,500 kW high-speed gas engine, GNB, a 2,000 kW high-efficiency and space-saving engine, and KU30GSI, a 3,650 to 5,750 kW medium-speed gas engine, thereby providing products that can be used for various applications from small-scale

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distributed power sources, CHPs for facilities and factories, to commercial power generation. **Figure 1** shows the power output range and external view of the MHIET gas engines.

MHIET is continuously working to improve the power generation efficiency of gas engines and to use waste heat for effective energy utilization. In addition, MHIET has begun technological efforts to utilize renewable energy and to achieve power generation using hydrogen to realize a de-carbonized society.

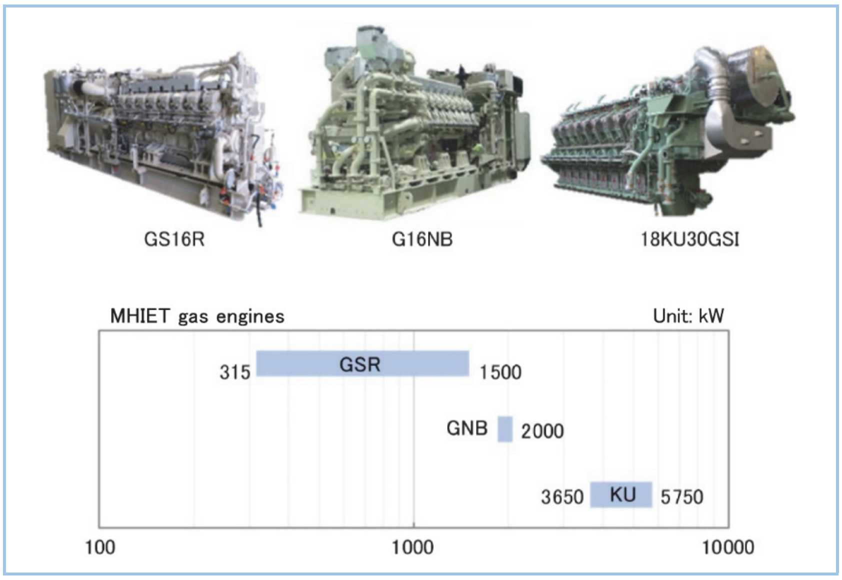

Figure 1 Power output range and external view of MHIET gas engines

2. Overview of KU gas engine

MHIET's KU gas engines have been developed continuously in pursuit of economy and reliability since the spark-ignited KU30G brought to the market in 1990, followed by the micro pilot-ignited KU30GA (MACH-30G) launched in 2001, and the spark-ignited KU30GSI released in 2009. The latest models, the KU30GSI series, consists of the KU30GSI, which focuses on overall efficiency, and the KU30GSI-PLUS, which focuses on power generation efficiency, covering an output range of 3,650 to 5,750 kW [(1), (2)]. **Table 1** shows the main specifications of the KU30GSI series.

The longest operating hours of the KU gas engine series have reached 180,000 hours, and the total operating hours of all KU series engines in the field have reached 11 million hours. The KU gas engines share about 80% of their components with the series products to ensure high reliability, thereby achieving products and services based on abundant experience in operation and maintenance.

Table 1 KU30GSI series main specifications

Type		KU30GSI	KU30GSI-PLUS
Number of cylinders		12 / 14 / 16 / 18	
Bore / Stroke	mm	300 x 380	
Engine speed	min^{-1}	720 / 750	
Power generation output *	kW	3,650 – 5,750	
Power generation efficiency *	%	46.5	49.5
NOx (O_2=0%)	ppm	< 320	
Weight	tons	40 - 60	

* Based on ISO3046 conditions and standard gases recommended by MHIET

3. Technology utilizing energy from gas engine cooling water

The KU30GSI achieves the world's highest level of overall efficiency for the combination of power generation and steam due to its increased power generation efficiency and raised exhaust gas temperature.

This engine can achieve an overall efficiency of over 80% when the use of steam and hot water is taken into account, and is widely used for CHPs. Effective use of energy leads to reduced fuel costs by reducing the energy used, which also contributes to CO_2 reduction. On the other hand, hot water cannot be used effectively throughout the year due to constraints on the demand side in some cases, resulting in situations where the benefits of in-house power generation facilities could not be maximized. To solve this, four companies* jointly developed a system in which the temperature of engine cooling water is raised to 120°C, above the boiling point, for use as a heat source, and the low-pressure steam generated is compressed and added to the steam produced by the exhaust gas boiler, etc. This gas engine CGS with all steam recovery was commercialized in 2015, and the 18KU30GSI increased steam generation from about 3.3 tons/h to about 5.1 tons/h, an increase of more than 1.5 times. The achieved overall efficiency of power generation and steam, excluding hot water, is more than 70%, the highest in the world. The gas engine CGS with all steam recovery provides a thermoelectric energy balance that cannot be obtained with the conventional gas engine CHP while maintaining high power generation efficiency, and the steam-generating capacity is equivalent to the lower limit level of a gas turbine for cogeneration.

The gas engine CGS with all steam recovery started field operation in 2018 and has since been in rated continuous operation for about 7 years, reaching more than 50,000 hours of operation. During the operation, no abnormal wear of parts or increase in lubricant consumption has been observed, and the engine has been running stably without any changes to the originally planned maintenance program. **Figure 2** shows the condition of the combustion chamber.

* Tokyo Gas Co., Ltd., Mitsubishi Heavy Industries, Ltd., Miura Co., Ltd., and Kobe Steel, Ltd.

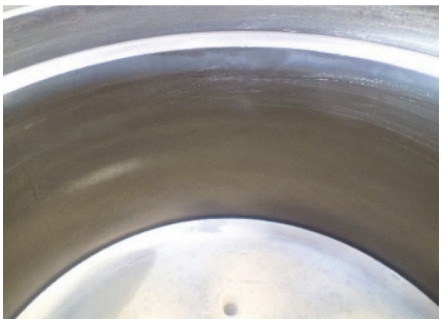

Figure 2　Condition of combustion chamber of gas engine CGS with all steam recovery

4. Technology to utilize hydrogen for gas engines

One technical challenge in utilizing hydrogen for gas engines for power generation is its combustion characteristics. Compared to the city gas 13A, hydrogen has a wider combustible range, faster combustion speed, and lower minimum ignition energy. This makes abnormal combustion such as knocking, pre-ignition, and backfiring more likely to occur in the engine. To effectively utilize energy in CHPs, it is necessary to maintain high power output and power generation efficiency while maintaining a high exhaust gas temperature during hydrogen co-firing. Using a single-cylinder test engine of the KU30GSI, MHIET understood the effects of mixing hydrogen with fuel gas equivalent to the city gas 13A on the combustion characteristics and investigated the effects on engine performance.

(1) Single-cylinder test engine and test details

The single-cylinder test engine used for the test employed the combustion chamber parts of the KU30GSI production models as they were. **Table 2** shows the main specifications and **Figure 3** shows the configuration of the test engine. Using a mixture of base fuel gas equivalent to the city gas 13A and 30 to 50 vol% hydrogen, the hydrogen co-firing test was conducted.

As an example of the tests conducted, an engine expansion ratio change test for the purpose of understanding the effect of hydrogen co-firing on abnormal combustion is shown below. The expansion ratio is the ratio of the cylinder volume at the bottom dead center to the cylinder volume at the top dead center. **Table 3** shows the test cases for the expansion ratio test. In Case 2, the intake valve close timing was retarded so that the actual compression ratio, which is the ratio of the cylinder volume at the intake valve close timing to the cylinder volume at the top dead center, was the same as in Case 1.

Tests were conducted with different excess air ratios and ignition timings in addition to the expansion ratios to select specifications that would ensure stable combustion.

Table 2 Specifications of single-cylinder test engine

Number of cylinders	1
Bore [mm]	300
Stroke [mm]	380
Displacement [L]	26.9
Engine speed [min^{-1}]	750
Combustion system	Pre-chamber lean-burn Spark ignition

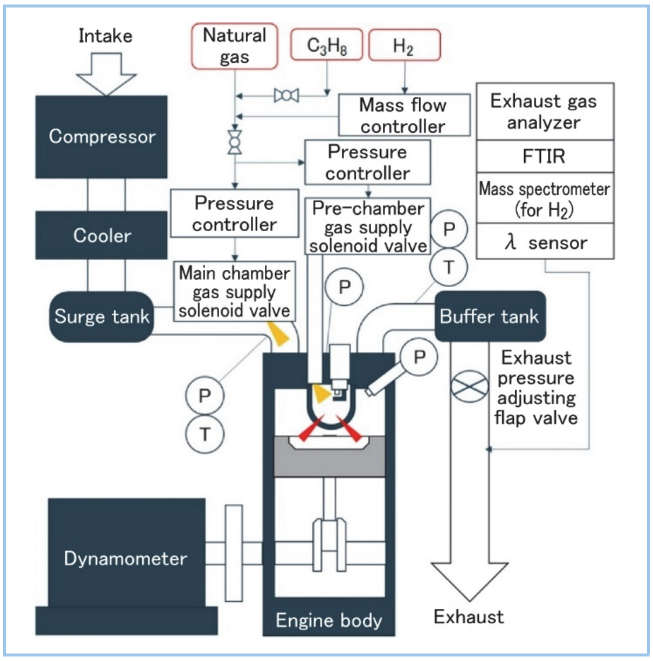

Figure 3 Diagram of test facilities

Table 3 Tested engine specification

		Base	Case 1	Case 2
Expansion ratio	–	Base	-0.5	-1.5
IVC*	–	Base	Base	14 deg. retarded

Each value represents difference from base specification
* IVC: Intake Valve Close timing

(2) Technology applied for combustion stabilization

Due to its combustion characteristics described above, hydrogen has a higher risk of pre-ignition than the city gas 13A. **Figure 4** shows an example of the in-cylinder pressure when pre-ignition occurred. In this figure, the solid lines represent the pressure of normal combustion, and the dotted lines represent the pressure of pre-ignition. In normal conditions, combustion in the pre-chamber started after the ignition command was given, but in the case of pre-ignition, combustion in the pre-chamber started before the ignition command was given, resulting in an increase in the maximum pressure in the main chamber. The occurrence of pre-ignition not only leads to an increase in the cylinder pressure, but also to an increase in the cylinder temperature and combustion chamber component temperatures, and in cases where pre-ignition occurs continuously, it may result in damage to combustion chamber components.

Figure 5 shows the occurrence rate of pre-ignition at rated load operation for each of the cases shown in Table 3. In the case of the base setting with a hydrogen co-firing rate of 50 vol%, the occurrence rate of pre-ignition exceeded 4% even when the excess air ratio, which is an index of the amount of air to fuel gas, was set high to slow down the combustion rate. On the other hand, the occurrence rate of pre-ignition could be suppressed by reducing the expansion ratio, and it was confirmed that reducing the expansion ratio to that of Case 2 suppressed the occurrence of pre-ignition even under fuel-rich conditions with a low excess air ratio. It is assumed that pre-ignition is caused by a mechanism in which oil droplets or other substances inside the cylinder spark during a compression stroke and cause flame spread, and optimizing the expansion ratio can suppress pre-ignition as shown in the results of this test.

In addition, it was confirmed that stable combustion can be achieved while maintaining the rated output from operation with the city gas 13A even when the hydrogen co-firing rate is increased to 50 vol% by applying technologies to control the gas supply timing appropriately and to control the combustion start timing and maximum pressure in the cylinder appropriately. MHIET is now in the design stage for commercialization of the technologies.

These technologies for combustion stabilization in hydrogen utilization are also effective for hydrogen co-firing in gas engine CGS with all steam recovery. To achieve hydrogen co-firing in gas engine CGS with all steam recovery, the engine cooling water system of a single-cylinder test engine was modified, and hydrogen co-firing tests with the cooling water temperature raised to 120°C were conducted. The higher cooling water temperature increases the wall temperature of the combustion chamber, causing abnormal combustion to be more likely to occur, but it was verified that the application of combustion stabilization technologies enabled hydrogen co-firing operation. We are also planning to commercialize hydrogen co-firing gas engine CGS with all steam recovery.

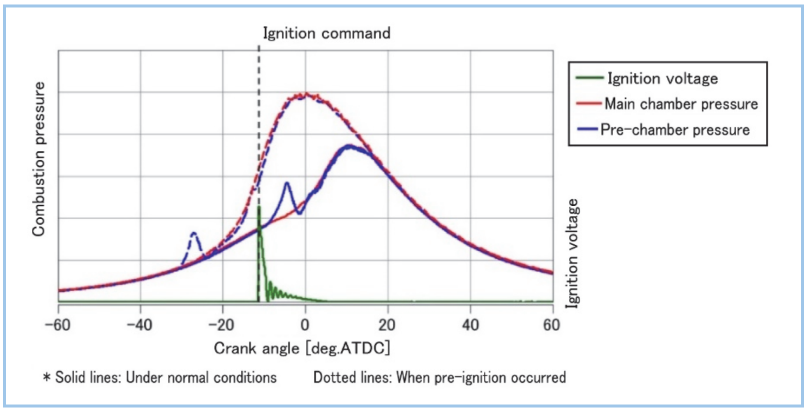

Figure 4 Cylinder pressure of pre-ignition cycle

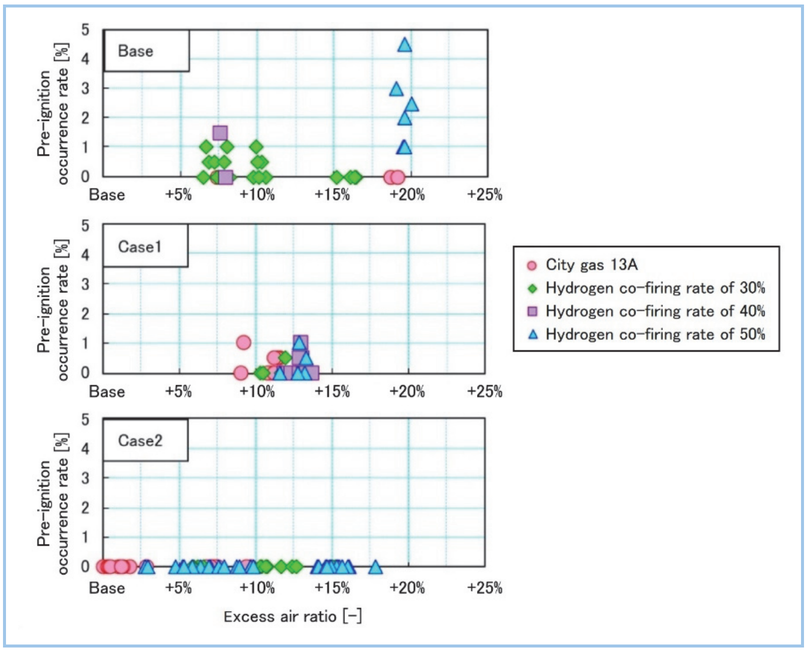

Figure 5 Pre-ignition occurrence rate in each test case

(3) Performance of actual equipment and CO_2 emission factor

Figure 6 shows the performance of actual equipment in hydrogen co-firing estimated from combustion tests using the single-cylinder test engine. Assuming that the maximum pressure in the cylinder is the same as that when the city gas 13A is used, the decrease in power generation efficiency in hydrogen co-firing compared to that in firing the city gas 13A would be only 0.5% or less, regardless of the co-firing ratio. Due to the excess air ratio increasing for stable combustion in hydrogen co-firing, the exhaust gas temperature at the turbocharger outlet in the case of hydrogen co-firing at the co-firing rate of 50 vol% would be about 30°C lower than that in the case of firing the city gas 13A. This decrease in exhaust gas temperature results in a decrease in the amount of steam obtained from the exhaust gas, but the CO_2 emission factor for power generation and steam utilization improves when the hydrogen co-firing rate is increased. **Figure 7** shows the results of the CO_2 emission factors (3), (4) for hydrogen co-firing.

The EU has established the EU Taxonomy, which systematically organizes environmentally sustainable economic activities, for the first time in the world, and stipulated that the direct CO_2 emissions of gas-fired thermal power projects that are allowed to be constructed by the end of 2030 should be less than 0.27 kg-CO_2/kWh (5). The emissions in the case of using only the city gas 13A would be 0.32 kg-CO_2/kWh, but it would be able to be reduced to 0.26 kg-CO_2/kWh in the case of hydrogen co-firing at the co-firing rate of 50 vol%.

It is estimated that with a gas engine CGS with all steam recovery, the CO_2 emission factor would be 0.28 kg-CO_2/kWh in the case of using only the city gas 13A without hydrogen co-firing, and could be reduced to 0.26 kg-CO_2/kWh in the case of hydrogen co-firing at the co-firing rate of 30 vol%.

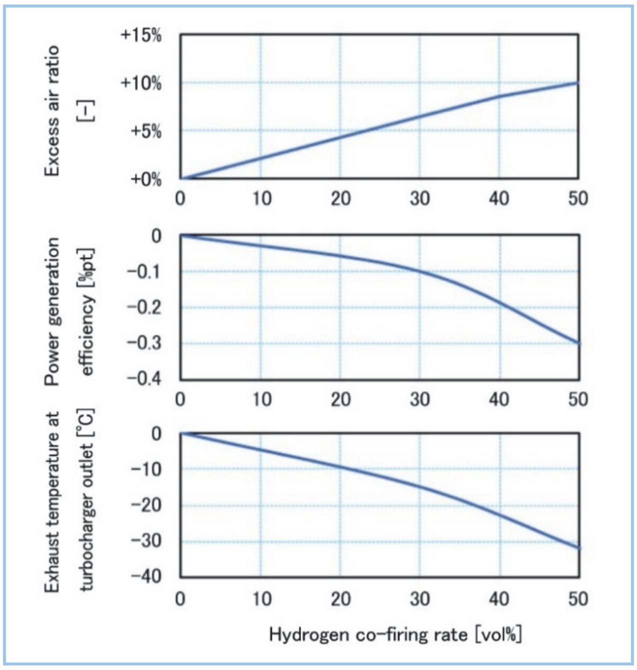

Figure 6 Prediction of engine performance in hydrogen co-firing

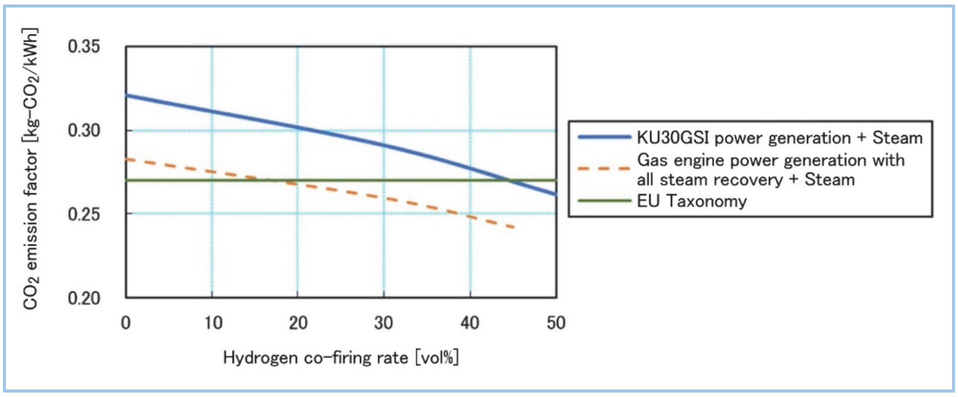

Figure 7 CO_2 emission factor from power generation and steam

5. Conclusion

We verified that gas engine CGS with all steam recovery achieves high engine system reliability and effective energy utilization during long-term operation. In addition, we have completed combustion tests at up to 50 vol% hydrogen co-firing rates in a single-cylinder test engine, and realized the prospect for future hydrogen utilization.

While addressing global warming on a global scale has become an issue, energy conservation and the use of unused energy are effective solutions. On the other hand, they have aspects of being difficult to achieve simultaneously with economic activities. We believe that gas engine cogeneration systems with highly efficient thermoelectricity utilization can be a solution.

To achieve carbon neutrality by 2050, the establishment of technology that can deal with a smooth transition to decarbonization while keeping costs low is anticipated. Gas engine cogeneration systems have the potential to be used with either hydrogen co-firing, hydrogen single-fuel firing, or synthetic methane, and we believe that they will be important systems that support energy demand in the future.

We have been promoting technological development of MHIET gas engines since their development to meet the needs of society and customers. We will continue to develop gas engine technology and provide solutions to meet the diverse needs of our customers.

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