CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 208

Kawasaki's gas engines powered by hydrogen for stationary generation

Fuels - Alternative & New Fuels

Akihito Aota, Kawasaki Heavy Industries, Ltd.

Yoshishige Sakai, Kawasaki Heavy Industries, Ltd
Takashi Horie, Kawasaki Heavy Industries, Ltd
Tatsuro Tanikawa, Kawasaki Heavy Industries, Ltd
Shinji Ito, Kawasaki Heavy Industries, Ltd

ABSTRACT

Kawasaki Heavy Industries, Ltd. has developed the Kawasaki Green Gas Engine in house based on the concepts of high efficiency and low NOx emissions, for stationary power generation and CHP applications. The Kawasaki KG engine is a four-stroke, spark-ignited, turbocharged gas engine. It is available in twelve- and 18-cylinder configurations and its power output ranges from 5.0 to 7.8 MW at 720 and 750 rpm. With the aim of further expanding hydrogen-based energy in order to achieve a carbon-neutral society, we are developing gas engines that are fueled by 30% hydrogen in volume with natural gas.

Kawasaki has successfully built a hydrogen suppling system onto the existing power plant with a 7.5MW gas engine (engine model: KG-18-T) which used city gas as fuel gas in Kobe works. A high-pressure hydrogen gas trailer is used for a tank of its system. A hydrogen blending system is also installed and controlled by an engine control system. Its blending ability from 5% to 30% was confirmed. Engine performances and emissions were measured under modified engine specifications at rated load (7.5 MW). Excellent results are observed through the measurement and those results are introduced in this paper. Now Kawasaki can offer gas engines named KG-18-T.HM which are capable of up to 30% of hydrogen admixture, and also retrofit kits for existing gas engines in the market.

Moreover, Kawasaki keeps developing hydrogen combustion technologies for gas engines for future generations. Single-cylinder engine tests were successfully carried out and the engine has already been operated with 100% hydrogen at rated load which is equivalent to 7.8 MW of a 18-cylinder engine. Fuel gas change over from 100% city gas to 100% hydrogen has also been enabled. Some of the significant achievements are introduced in this paper.

1 INTRODUCTION

Kawasaki developed the Kawasaki Green Gas Engine (KG series), a high-performance gas engine with high efficiency and low NOx emission. It launched it into the market in 2007.[1] Since then, we have continued to develop the KG-18-V series,[2] which applies a turbocharger with a variable nozzle to increase electrical efficiency, and the KG-18-T series,[3] which is equipped with a two-stage turbocharging system to improve more efficiency. The state-of-the-art KG-18-T series (Figure 1) has achieved the world's highest level of electrical efficiency of 51.0%, contributing to further reductions in fuel gas consumption and CO_2 emissions. The KG series is characterized by high partial load performance, low NOx emission, and high reliability with a common main structure from KG. Orders for the KG series and the KG-T series have been steadily received, and more than 200 units have been delivered to the market so far.

Figure 1. KG-18-T gas engine

In 2020, the Japanese government announced that it would aim for carbon neutrality, which would reduce greenhouse gas emissions to zero by 2050. As of April 2021, 125 countries and one region have announced their intention to become carbon neutral. We Kawasaki continues to propose the Kawasaki Green Gas Engine as a power generation facility that can reduce CO_2 emissions by reducing fuel consumption such as city gas/natural gas and heat sources. At the same time, we are also working on technology development to apply hydrogen to fuel gas as a future carbon neutral technology.

We have single cylinder test engines for development, which is configured with an equivalent to one cylinder of the Kawasaki green gas engine and can be tested under operating conditions equivalent to the same combustion load as the KG or KG-T series actual engines. The main dimensions of the engine, such as bore and stroke, are the same as those of Kawasaki green gas engines. In the development to apply 30% hydrogen admixture, this single cylinder test engine was used to optimize combustion such as cam timing and compression ratio.

This paper presents the results of the actual test of a KG-18-T.HM engine which can accept 30% hydrogen admixture as fuel gas at the Kobe Plant and the test with 100% hydrogen as the future technology, as the challenge of applying hydrogen at the single cylinder engine.

2 FEATURES OF GAS ENGINE

Kawasaki Green Gas Engines are medium-speed four-stroke engines that employ spark ignition, a prechamber combustion, and port fuel injection (PFI) system (See Figure 2). Its engine output is between 5 and 7.8 MW (Table 1), and they are suitable for both engine power plants and CHP generations. Independent control of the amount of gas fuel injected into the main and prechambers enables optimization of the injection timing and air-fuel ratio for each chamber. Furthermore, controlling the ignition timing for each cylinder keeps its cylinder conditions optimized, to maximize electric efficiency.

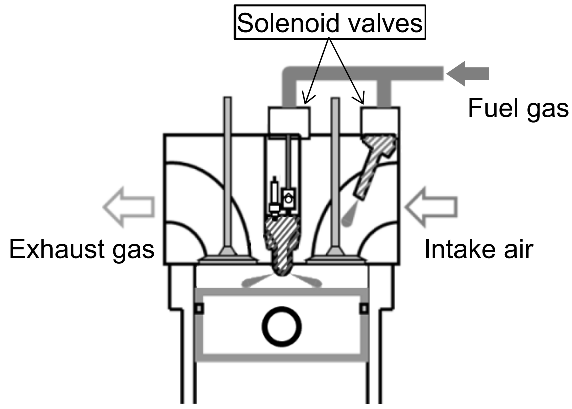


Figure 2. Fuel supply and ignition system

Table 1. Technical data of KG engines

Engine Model	KG-12	KG-18	KG-18-V	KG-18-T
Electric output [kW]	5200 / 5000	7800 / 7500		
Electric efficiency	48.5%		49.5%	51.0%
Speed [rpm]	750 / 720			
Frequency [Hz]	50 / 60			
No. of Cylinders	12	18		
Bore [mm]	300			
Stroke [mm]	480			

3 HYDROGEN GAS AS FUEL

Hydrogen fuel offers the advantage of zero CO_2 emissions during combustion. The main properties of Japan's city gas 13A, methane and hydrogen gas[4] are shown in Table 2. Hydrogen has a very low minimum ignition energy and high laminar flame speed, and its wide flammable range. These properties will easily cause abnormal combustion, when used as fuel in engines.

Table 2. Properties of typical fuel gases

		City gas 13A	CH_4	H_2
CH_4	vol%	89.6	100	0.0
CxHy	vol%	10.4	0.0	0.0
H_2	vol%	0.0	0.0	100
LHV	MJ/Nm^3	40.6	35.8	10.8
Minimum ignition energy	mJ	-	0.29	0.017
Laminar flame speed	cm/s	35～47	38	350
MN	-	69	100	0
LEL / UEL	%	-	5 - 15	4 - 75

Here are examples of abnormal combustion that occurred during testing. A backfire phenomenon can be observed in Figure 3. A pre-ignition is measured in Figure 4. And Heavy knock is observed in Figure 5. In the worst case, these abnormal combustions can lead to engine damages.

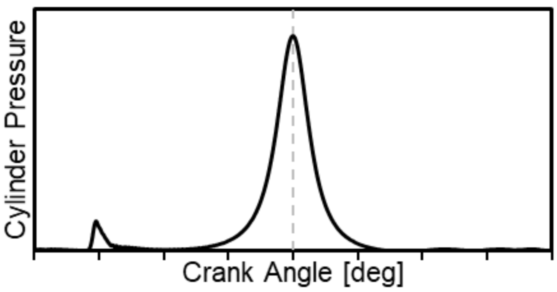


Figure 3. Backfire: Combustion of the fuel gas before intake valve closed

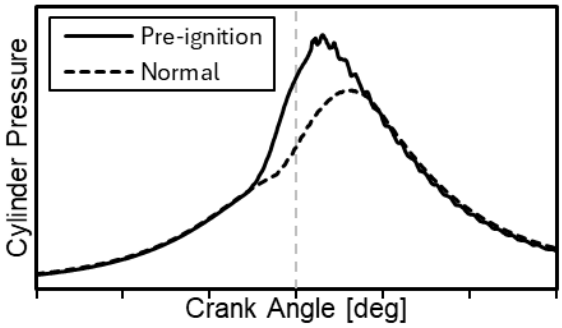


Figure 4. Pre-ignition: Combustion of the fuel gas before intended ignition timing

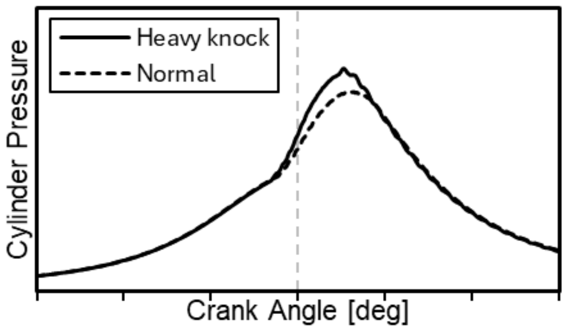


Figure 5. Heavy knock

4 GAS ENEINGE FOR 30% HYDROGEN

4.1 Addition of hydrogen supply facilities

As mentioned above, we conducted a test using 30% hydrogen in a single-cylinder test engine and developed a combustion technology that enables stable operation. After that, the risk reduction study and trial manufacture evaluation in the hydrogen leakage prevention for the safe application of hydrogen to the actual engine were carried out, and the prospect of the application to the actual engine of Kawasaki green gas engine was established in terms of combustion technology and safety measures.

Our company and Kobe plants manufacture Kawasaki green gas engines, energy plant equipment such as aerodynamic machinery, marine propulsion products, and marine equipment. In 2018, we installed a state-of-the-art KG-18 T gas engine power generation facility (rated output: 7500 kW) to supply electricity for operations at the Kobe Plant and to develop and evaluate gas engines. It has been operated as the Kobe Power Center using city gas 13A as fuel. Therefore, it was decided to install additional hydrogen supply facilities in the KG-18 T engine and to proceed with verification of 30% hydrogen co-firing in full scale.

In 2024, a high-pressure gas storage facility was constructed to accommodate two hydrogen gas trailers. Figure 6 shows the appearance of the completed facility.

Figure 6. Kobe Power Center with completed hydrogen supply facility

Hydrogen gas is supplied to the hydrogen mixing unit after reducing the pressure to less than 1 MPa in the trailer receiving unit in the high-pressure gas storage facility. In the hydrogen mixing unit, hydrogen gas and city gas are supplied and controlled by a flow control valve so that the mixing ratio can be set arbitrarily at 5~30%, and uniformly mixed as fuel gas. The ability of the hydrogen mixing unit to properly mix hydrogen and city gas was verified by utilizing CFD analysis technology of our company which is also used in gas turbines and motorcycle engines. An example of CFD is shown in Figure 7. It can be confirmed that city gas and hydrogen are mixed uniformly by passing through the mixer.

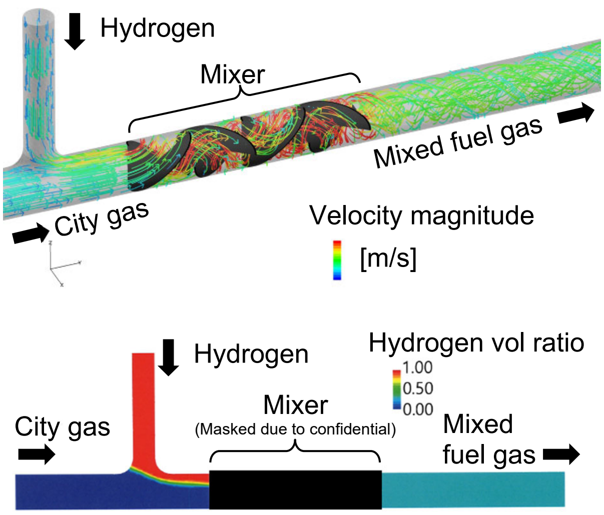


Figure 7. An example of CFD analysis for evaluation of mixing ability

The mixed fuel gas is supplied to a gas engine through a KGG module. KGG module is a fuel gas control device, consisting of emergency shut-off valves and a pressure relief valve.

A typical hydrogen gas trailer in Japan has a maximum filling pressure of 19.6MPa, a volume of approximately 15m^3, and a maximum hydrogen payload of 3000Nm^3. One hydrogen gas trailer enables to run a gas engine at rated power for approximately four hours. The size of the hydrogen gas trailer parking space in the Kobe Power Center is about 15m × 10m. Figure 8 shows the arrangement of equipment in the Kobe Power Center. Kawasaki can offer the power plant package, including not only gas engines but also auxiliary equipment such as hydrogen mixing units or KGG modules.

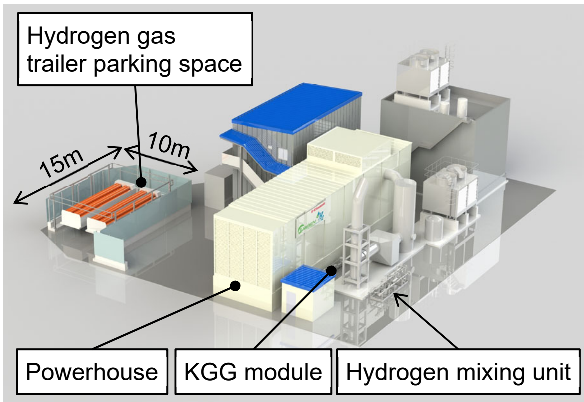


Figure 8. Arrangement in Kobe Power Center

4.2 30% Hydrogen compatibility with engine

The method for dealing with hydrogen shown below in 4.2.1 and 4.2.2 can be easily applied to an existing gas engine already in operation by retrofitting them. Actually, they were applied to the existing KG-18-T engine, which were in operation, at the Kobe Power Center by retrofitting.

4.2.1 Measures for hydrogen combustion characteristics

In terms of combustion control, it is based on the original city gas and natural gas engine combustion control, and safety features have been added against to abnormal combustion and to prevent flue explosions. Furthermore, stable combustion condition was realized by controlling injection timing in response to both engine load and the hydrogen mixing ratio.

In terms of combustion, hydrogen burns quickly and is easily ignited with little energy, which tends to cause abnormal combustion such as knocking. In the single cylinder test machine, it was confirmed that both frequency and intensity of knocking increased when 30% hydrogen was mixed with city gas 13A. Therefore, when 30% hydrogen admixture is to the existing Kawasaki green gas engine, it is necessary to limit the power output up to 80% of the rated output (In the case of 7500 kW type city gas firing, the maximum power generation output of 30% hydrogen admixture is 6000 kW.).

By reducing the compression ratio and optimizing the turbocharger specifications, the KG-18-T engine at the Kobe Power Center achieved a rated output of 7500kW without limiting the power generation output even in the case of 30% hydrogen admixture while avoiding knocking. Because the combustion specification of this engine was changed, the new engine model's name "KG-18-T.HM" was given.

The upper graph of Figure 9 shows the cylinder pressure curve, and the lower shows a comparison of heat release. In the KG-18-T.HM, by optimizing the ignition timing according to the hydrogen ratio, the peak cylinder pressure of the hydrogen 30% operation mode is same as that of city gas operation mode of the original engine KG-18-T, despite the rapid heat release that is unique to hydrogen combustion. Meanwhile, in the KG-18-T.HM city gas mode, the electrical efficiency was recovered by advancing the ignition timing.

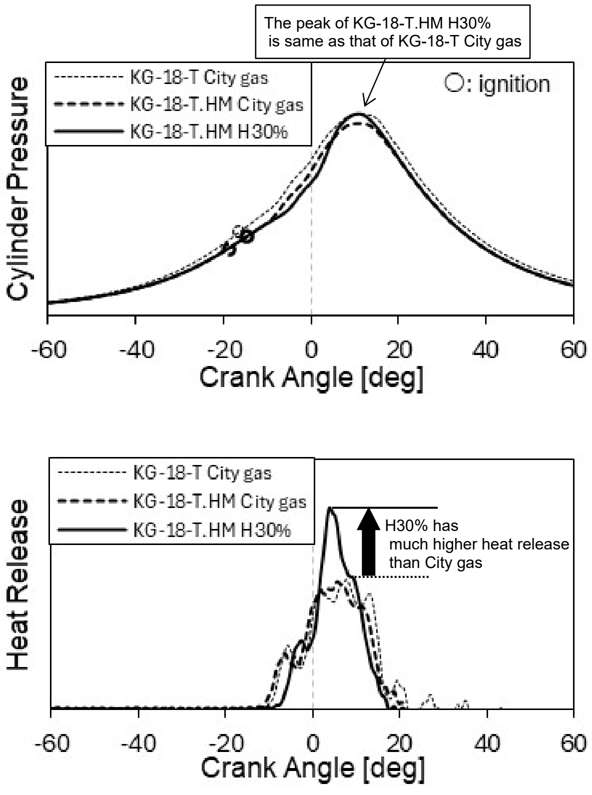


Figure 9. Cylinder Pressure and Heat Release Curve comparing KG-18-T and KG-18-T.HM

As the result, despite of the lower compression ratio, a high electrical efficiency was achieved in both operating mode; the city gas mode and hydrogen 30% admixture mode, almost equivalent to the efficiency (51.0%) of the base model KG-18-T.

The amount of NOx generation was about 200ppm (corrected to O_2 = 0%) in the case of city gas mode, and it tended to increase about 50ppm in the 30% hydrogen admixture compared with the case of city gas mode. Figure 10 shows the NOx emission measurement results at rated output (7500kW). Exhaust gas temperature and exhaust gas air volume are almost the same in both operation mode, and the same amount of exhaust heat recovery is expected.

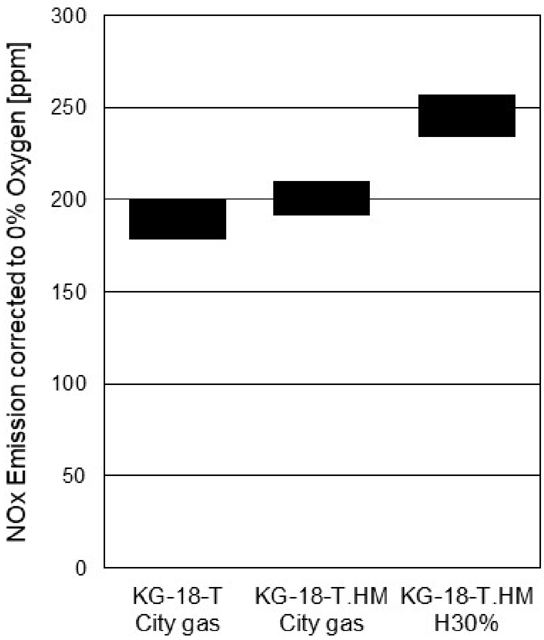


Figure 10. NOx Emission measurement results

4.2.2 Measures to reduce the risk of hydrogen leakage

Hydrogen has a wide flammable range and is easily ignited with little energy. In order to use it safely as a fuel, it is important to reduce the risk of fuel gas leakage and to take measures safely in case of leakage. At the Kobe Power Center, the main part of the fuel gas piping of the gas engine was replaced with a welded one. A flange cover is provided on the piping flange of the remaining fuel gas, a leakage detection cover is provided integrally covering a portion around the cylinder head where there are many fuel gas pipes, and gas detectors are installed on the flange covers and the leakage detection covers. In addition, to prevent remaining of leaked fuel gas in the leak detection cover, a fan is constantly ventilated. These modifications and added parts onto the engine are indicated in Figure 11. And a photo of KG-18-T.HM retrofitted from KG-18-T in Kobe Power Centre are shown in Figure 12. Figure 13 shows the whole image of KG-18-T.HM engine.

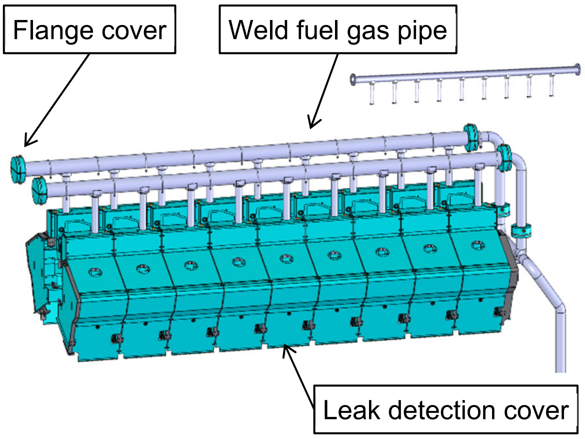


Figure 11. modification and added parts to reduce the risk of hydrogen leakage on engine

Figure 12. a photo of the engine retrofitted from KG-18-T to KG-18-T.HM in Kobe Power Centre

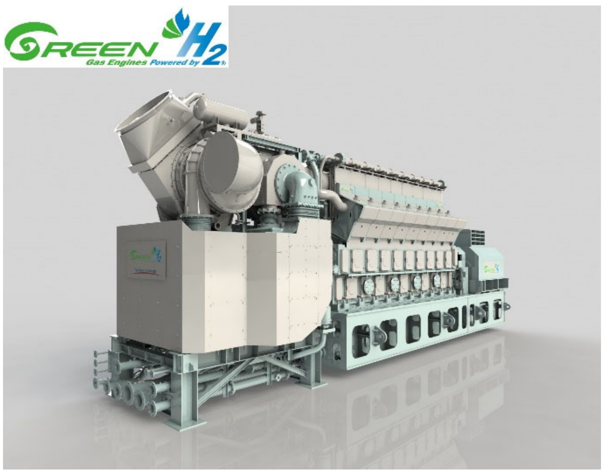


Figure 13. 3D image of KG-18-T.HM

5 FUNCTIONAL VERIFICATION OPERATION AT KOBE POWER CENTER

As described above, the combustion adjustment in the steady state operation was completed, and the verification of the operability as a power generation engine continued in the actual plant. It was confirmed that the same load increasing rate and load decreasing rate as those of city gas can be applied by optimization of combustion control even in 30% hydrogen admixture mode.

It was also confirmed that the hydrogen mixing rate can be controlled according to the commanded value input via engine control system at a representative point within the range of acceptable hydrogen mixing ratio - load map. An example of measurement results is shown in Figure 14. It shows the actual mixing ratio when the hydrogen ratio was ordered to increase from 0% to 30% at 7500kW. This result means that flexible operation is possible in accordance with to the remaining amount of hydrogen in a tank (gas trailer) and/or the hydrogen supply amount.

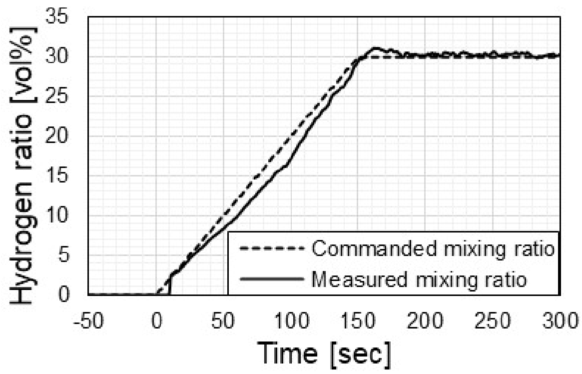


Figure 14. An example of hydrogen mixing ratio

A governor test was carried out under the 30% hydrogen admixture mode, and it was confirmed that the fluctuation of rotational speed was within criteria, and it was the almost same result as the result of city gas 13A mode.

A series of test were completed at the end of September, and the plant started operation in October as a power generation facility that can use up to 30% hydrogen. This is the first powerplant with large gas engine in Japan that hydrogen is used as fuel.

6 HYDROGEN FIRING TEST AS A FUTURE TECHNOLOGY

In order to further reduce CO_2 emissions, development is underway to apply more than 30% hydrogen to engines. As a part of the elemental test, a test in which 100% hydrogen gas was applied to a single cylinder testing engine was carried out. A photo of the single cylinder test engine is shown in Figure 15.

Figure 15. A photo of the single-cylinder test engine

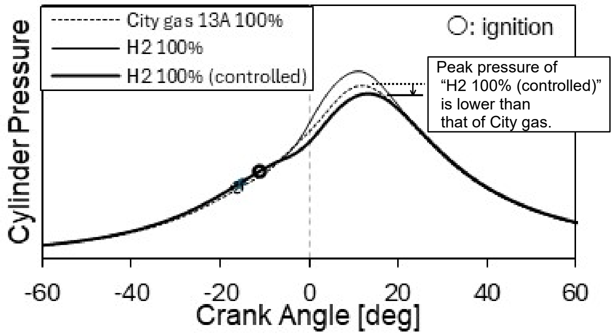
The same prechamber and ignition plug as the Kawasaki Green gas engines are installed. And its compression ratio has been further optimized to suit the combustion characteristics of hydrogen.

EGR was applied as a measure to moderate the rapid combustion characteristic of hydrogen. The obtained cylinder pressure and heat release traces are shown as “H2 100%” in Figure 16. Furthermore, the ignition timing and the amount of fuel gas supplied to the prechamber were appropriately controlled (Please see “H2 100% (controlled)” in the Fig.16). For comparison, the measurement result fueled by city gas “without” EGR is also indicated (Please see “City gas 13A 100%” in Fig. 16).

As a result, it was confirmed that it was possible to operate on 100% hydrogen at a IMEP equivalent to the rated output. Furthermore, fuel changeover from 100% city gas 13A to 100% hydrogen was succeeded while keeping same IMEP (rated output).

Until the hydrogen supply network is established, it is desirable to have an engine that can run on both city gas/natural gas and hydrogen. A realistic prospect was obtained from the viewpoint of combustion.

Hydrogen combustion methods are not limited to PFI system and other combustion methods are also possible. Kawasaki will proceed elementally testing of combustion technologies to comprehend what is best solution for hydrogen. And we are targeting to launch the pure hydrogen engines around 2030.



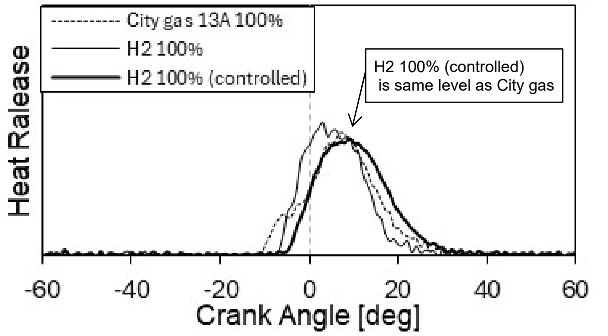


Figure 16. an example of Cylinder Pressure curves and Heat Release of the SCE test results

7 CONCLUSIONS

Kawasaki have developed a gas engine capable of 30% hydrogen admixture and have begun operation at the Kobe Power Centre as a pilot plant. This series of developments has also demonstrated not only that hydrogen can be applied to the Kawasaki green gas engine, but also that it is possible to retrofit existing gas engine power generation which uses natural gas as fuel to be capable of 30% hydrogen admixture.

30% hydrogen applicable gas engines and retrofitting of engines already delivered to customers are scheduled to launch in 2025. Kawasaki intend to contribute to the realization of carbon neutrality through providing hydrogen admixture gas engines and, in near future, pure hydrogen gas engines.

8 DEFINITIONS, ACRONOYMS, ABBREVIATIONS

CFD	**Computational Fluid Dynamics**
CHP	Combined Heat and Power
CH4	Methane
CxHy	Hydrocarbon
H2	Hydrogen
LHV	Lower Heat Value
LEL	Lower Explosive Limit
MN	Methane Number
PFI	Port Fuel Injection
UEL	Upper Explosive Limit

9 REFERENCES

[1] Hideaki Sakurai, Tomohiko Sugimoto, Yoshishige Sakai, Tetsuo Tokuoka, Yoshiharu Nonaka, Manabu Honjou and Takashi Horie, 2010. "Newly Developed Kawasaki Green Gas Engine – Top performance GE", *CIMAC congress 2010,* Bergen, Paper No. 189.

[2] Tomohiko Sugimoto, Yoshishige Sakai, Takashi Hattori, Takashi Horie and Yousuke Nonaka, 2013. "Gas engine with world highest generating efficiency – Green gas engine", *Kawasaki Technical Review,* No.173, 27-32.

[3] Takashi Horie, Yoshishige Sakai, Michio Fukushima, Yohei Tsuji, Sekai Miyamoto, Tomohiro Sakamoto, 2019. "Development of Next Generation High Performance KG version 2 Gas Engine with Two Stage Turbocharging System", *CIMAC Congress 2019*, Vancouver, Paper No.225.

[4] CIMAC WG17, 2021, "H2 in Stationary 4-Stroke Gas Engines for Power Generation", *CIMAC Guideline*