Development of Hydrogen Co-firing and 100% Hydrogen Engines for Power Generation that Contribute to a Low-carbon and Decarbonized Society

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Towards achieving a low-carbon or carbon-neutral society, we are working on the development of reciprocating engines that use hydrogen as a fuel or co-fuel. Our hydrogen co-firing engine products are continuously operable on city gas 13A with a 15 vol% blend of hydrogen. In regard to the burning of 100% hydrogen in engines, the engine's specifications and control parameters were determined based on the results of numerical simulation and single-cylinder engine testing. A trial run of a newly built hydrogen engine generator set is now underway using hydrogen as a fuel at our factory premises; the demonstration has completed the sequence of phases in operation on 100% hydrogen from engine start to power generation at a rated output (435 kW).

1. Introduction

Mitsubishi Heavy Industries Engine & Turbocharger, Ltd. (hereinafter referred to as MHIET) has been providing diesel and gas engines with superior performance, reliability and environmental characteristics for power generation, marine and industrial vehicle applications. Towards achieving a low-carbon or carbon-neutral society, we are making combustion engines adapted to use hydrogen as a fuel or co-fuel, to enhance value for customers aiming for better environmental characteristics and energy transition.

In respect of hydrogen co-firing in engines, commercialization has been enabled by determining the engine's specification configurations and operating conditions in such a way that hydrogen-mixed fuel can be stably burned to generate power without making major changes to the specifications of existing city gas 13A-fired engines. For burning 100% hydrogen, the engine specifications enabling stable combustion without emitting greenhouse gases have been determined by utilizing numerical fluid and combustion simulation technologies and a single-cylinder test unit. A trial run of the demonstration facility is underway in-house. This report presents the current status in the development.

2. Features of our GSR gas engines

The hydrogen engine is based on our GSR gas engine series, whose reliability and efficiency in production and parts supply have been optimized, since their market release in 1991, by making about 80% of the parts used the same as the diesel engine serving as the base of GSR products. In GSR series, the power output per unit ranges from 315 kW to 1,500 kW. The application of the Miller cycle and lean-burn combustion has helped realize the highest power generation efficiencies in the same output classes. Moreover, because of their superior load input performance with pre-chamber spark ignition and black out start (BOS), the series are also used as equipment to satisfy the need for power supply security in times of emergency. A radiator version of the GSR lineup is also available to meet business continuity plan (BCP) demand, which is growing after the Great East Japan

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Earthquake. The GSR series may be used as a normal power source for high-rise buildings, factories, commercial facilities, hospitals and such, or a backup power source during peak-cut operation.

3. Hydrogen co-firing engines

3.1 Development of hydrogen co-firing engines

Together with Toho Gas Co., Ltd., MHIET has worked to develop a hydrogen co-firing engine using our GS6R2 gas engine. The impact of hydrogen blending on combustion performance and the effect of reducing greenhouse gases have been evaluated [(1), (2)]. The verification testing, in which operational patterns expected in the market were simulated, has confirmed the operability without risks such as abnormal combustion.

3.2 Commercialization of power generation set with hydrogen co-firing engine

As mentioned above, we have worked on the development of the SGP-M450 cogeneration system into which GS6R2 gas engines are incorporated. The system can run on hydrogen-mixed fuel. The main specifications are given in **Table 1**, while the schematic diagram is in **Figure 1**. The maximum ratio of hydrogen blending has been set at 15 vol%, to maintain the range of changes to the conventional gas engine at a minimum. This product is operable in either mode of single-fuel firing (i.e., city gas 13A) or co-firing with hydrogen. The operation mode can be switched between these two whenever needed during load operation.

Table 1 Main specifications of SGP-M450

Product model		SGP-M450
Engine model		GS6R2-PTK
Applicable fuel type		City gas 13A, or blended fuel of city gas 13A and hydrogen
Cylinder bore	mm	170
Stroke	mm	220
Rated output	kW	450
Rated rotation speed	min^{-1}	1,200
Brake mean effective pressure	MPa	1.55
Combustion system	NA	Pre-chamber lean-burn combustion
Ignition system	NA	Spark ignition

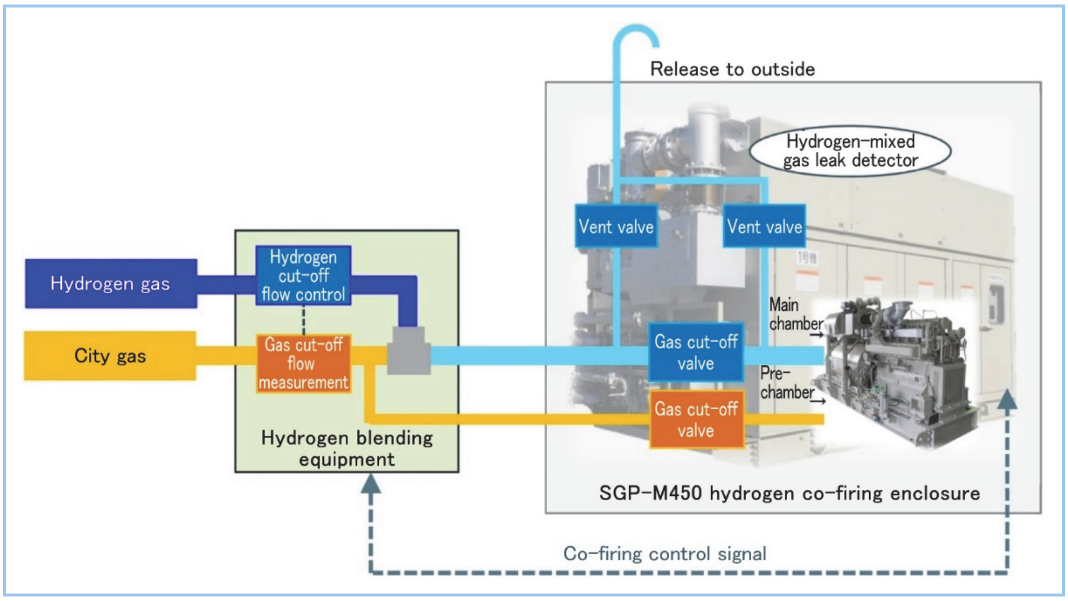

Figure 1 Schematic diagram of SGP-M450 system in co-firing mode

The power output by co-firing with hydrogen remains as high as the conventional single-fuel (city gas 13A) firing. Hydrogen is blended into city gas 13A before being sent into the enclosure. The fuel system is therefore designed to allow only the necessary amount of the blended fuel to pass through the pipes in the enclosure during co-firing operation, avoiding the risk of pure hydrogen leaking inside the enclosure. In our fuel feed system, the blended fuel is supplied only to the main chamber upstream of the engine turbocharger. The pre-chamber takes in only city gas 13A, as in the case of the current models of city gas 13A-fired engines. This feed system has enabled the levels of NOx emissions to be maintained at no more than 200 ppm (O_2 = 0%), which is comparable to conventional units, without compromising the power generation performance.

It has also been ensured that the performance in the single-fuel firing mode is comparable to conventional city gas 13A-fired engines, by adapting SGP-M450 to operate on hydrogen-mixed fuel without changing the specifications of combustion system parts and the turbocharger. Moreover, having been designed to run on city gas 13A during engine start-up, SGP-M450 exhibits performance as good as the city gas 13A-fired units in terms of the initial load input rate during stand-alone operation, which makes it possible to respond to BCP demand.

4. 100% hydrogen engine

As in the case of the hydrogen co-firing engine presented in section 3, the 100% hydrogen engine is also being developed from the lean-burn gas engine GSR series in our portfolio. When 100% hydrogen is fired, combustion takes place faster than co-firing, increasing the risk of abnormal combustion such as backfire, pre-ignition and knocking. The challenge, therefore, lies in stabilizing combustion and reducing the risk of such abnormal burning processes. Described below are our approaches to these issues and verification projects using an actual unit.

4.1 Performance optimization by single-cylinder hydrogen engine testing and analysis

In designing a full-scale 100% hydrogen engine based on our GSR gas engine series, we planned to optimize the performance of the engine within a short period of time by simultaneously working on the basic hydrogen combustion testing and numerical analysis. The hydrogen combustion testing was conducted as part of joint research with the National Institute of Advanced Industrial Science and Technology (hereinafter referred to as AIST), using their single-cylinder engine (**Figure 2**). The design process and the outcomes are summarized in a concrete manner below (**Figure 3**).

Firstly, a wide range of basic data including cylinder pressure and thermal efficiency of hydrogen combustion were obtained, while varying engine parts and control parameters, to acquire a broad insight into hydrogen combustion. Next came building an analysis model based on the obtained basic data. This was followed by the identification of rate-controlling parameters to design the performance of a 100% hydrogen engine and the optimization of engine specifications and control parameters to maximize marketability as a product. Lastly, the unit with the optimized specifications was used to conduct a single-cylinder engine test once again. The results include the realization of stable combustion of 100% hydrogen. It has also been confirmed that the thermal efficiency gains by 1.9%pts, as expected, while satisfying the conditions limited by factors such as knocking and NOx [(3)].

Thus, the specifications of the demonstration unit and the control parameters were determined based on these testing and analysis results to achieve stable combustion and optimal performance.

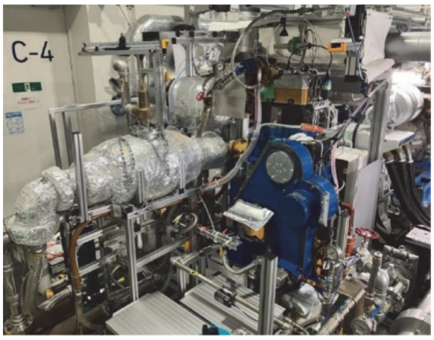

Figure 2 AIST's single-cylinder test engine

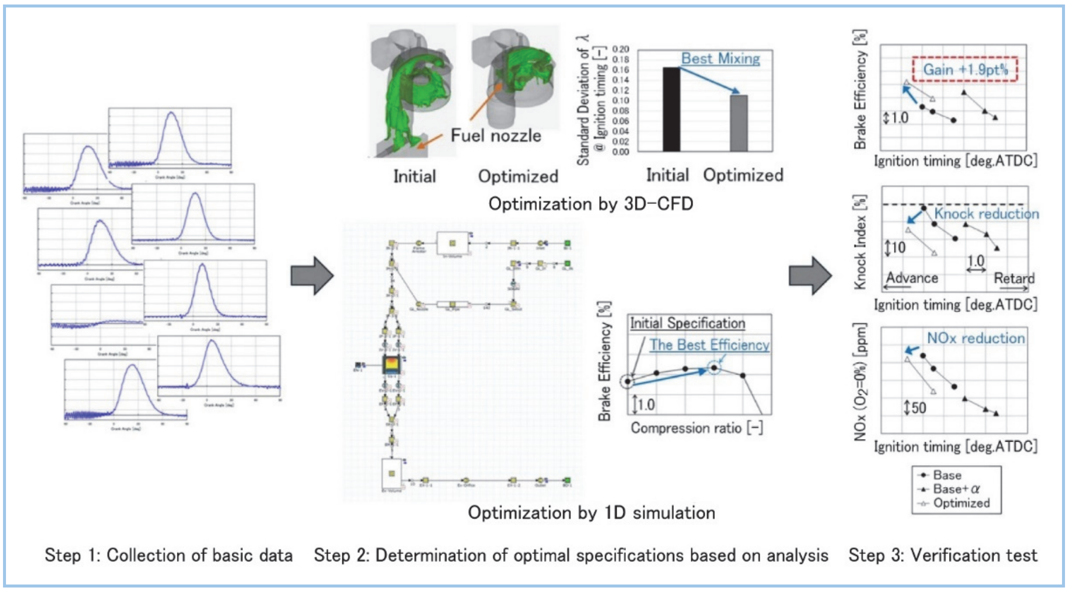

Figure 3 Design optimization by single-cylinder engine testing and analysis

4.2 Design of 100% hydrogen combustion engine

When compared to city gas 13A, hydrogen is particularly characterized by its tendency to leak out, high flammability and high combustion rate. These increase not only the risk of abnormal combustion in the engine's combustion chamber (knocking and pre-ignition) but also the risk of ignition at unintended locations in the engine (backfire and afterfire). Therefore, risk-reduction measures were taken during the design phase. The major changes from the GSR gas engine series are (1) adoption of an open chamber spark ignition system, (2) use of a cylinder pressure sensor, and (3) adoption of a port injection method (**Figure 4**) [2]. Adopting these concepts, the demonstration unit was designed based on the GS6R2 6-cylinder gas engine. **Table 2** shows the specifications, while **Figure 5** is a photograph of its exterior view. In regard to the power output and the brake mean effective pressure in the table, the numerical values given therein are just initial targets and will be further reviewed for higher performance. The major changes are detailed below.

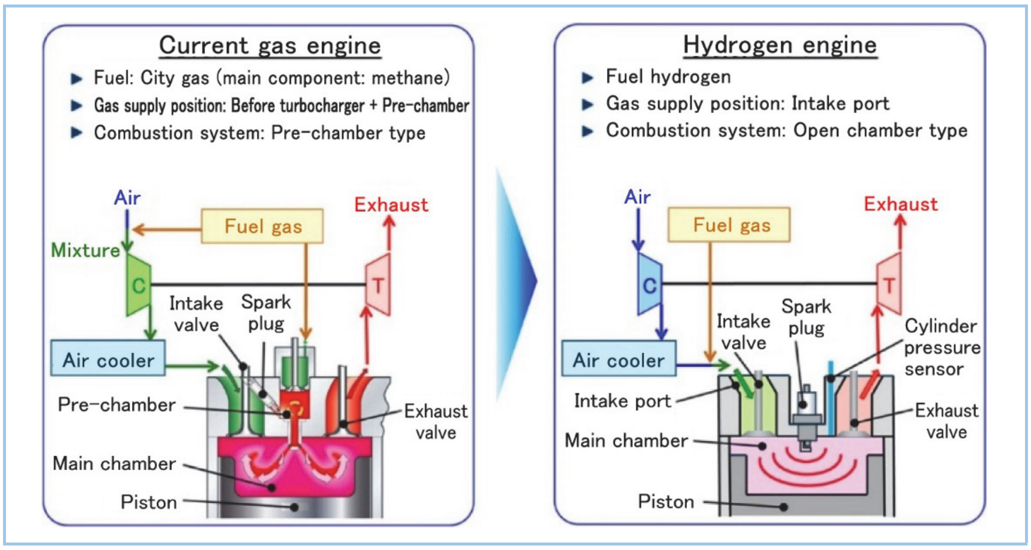

Figure 4 Changes made to 100% hydrogen combustion engine

Table 2 Specifications of 100% hydrogen combustion engine demonstration unit

Engine model		GS6R2-PTK
Applicable fuel type		100% hydrogen
Cylinder bore	mm	170
Stroke	mm	220
Rated output	kW	435
Rated rotation speed	min^{-1}	1,500
Brake mean effective pressure	MPa	1.2
Combustion system	NA	Open chamber lean-burn combustion
Ignition system	NA	Spark ignition

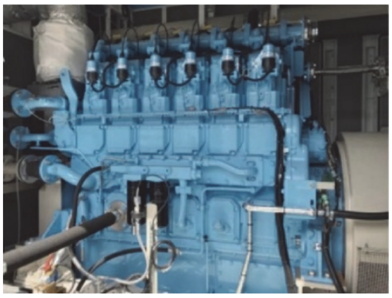

Figure 5 100% hydrogen combustion engine demonstration unit

(1) Open chamber spark ignition system

With the aim of controlling the fast combustion velocity of 100% hydrogen, an open chamber spark ignition system was adopted, in contrast to the conventional GSR series in which ignition is caused by a spark in the pre-chamber. Moreover, the compression ratio, intake valve closing timing, air excess ratio and other factors were reviewed to optimize the combustion rate and stabilize combustion.

(2) Cylinder pressure sensor

A cylinder pressure sensor was newly introduced in each cylinder of a 100% hydrogen engine. With the sensor equipped, abnormal combustion such as misfire, pre-ignition and knocking can be detected to promptly stop fuel supply, thereby avoiding the risk of damaging the engine.

(3) Port injection method

In the conventional GSR series, fuel is supplied upstream of the turbocharger from which the engine takes in the premixture of fuel and air. Meanwhile, in the 100% hydrogen engine, fuel is supplied to the intake port of each cylinder (port injection method). With this method, the distributed area of the premixture in the intake system can be minimized, thereby reducing the risk of damaging the engine if a backfire occurs.

4.3 Design of power generation set

Because of hydrogen's higher tendency to leak out or explode than city gas 13A, if it is to be used, it needs to be guaranteed that an explosion can be avoided even in the event of a leak, while engine operation is safely brought to a halt. An explosion will occur only when all three elements of the fire triangle are present, that is, fuel (hydrogen within the flammability range), oxygen (oxygen in air) and heat (fire, static electricity, high temperature, etc.). Therefore, the hydrogen engine generator set should be designed to prevent the simultaneous presence of the three elements, while reducing the potential of generating each of the elements. When it comes to hydrogen leakage, design is especially focused on no hydrogen leakage, promptly detecting leakage, if any, to stop the engine safely, and not allowing leaked hydrogen to stagnate. The safety is thus enhanced. As specific examples, how the enclosure and the hydrogen system were designed are presented below.

(1) Enclosure

Figure 6 shows the enclosure of 100% hydrogen combustion engine. The ventilation fan will always be in operation when hydrogen is present in the fuel pipes inside the enclosure. If hydrogen leaks while the fan is off, the specially designed roof will allow hydrogen to be naturally released outside the enclosure. The gas leak detectors for hydrogen and city gas 13A and a fire alarm are also installed inside the enclosure.

(2) Hydrogen system

The fuel piping system inside the enclosure is equipped with double shut-off valves and other control valves necessary for engine control. Hydrogen stays in the pipes after the engine is stopped. To reduce the risk of hydrogen leaking within the enclosure, a vent system and a nitrogen purge system were introduced in the fuel piping system. With these, hydrogen can be automatically vented and nitrogen-purged after the engine stops, respectively. The risk of ignition by static electricity was also reduced by bonding the fuel pipe flanges and getting them grounded.

Figure 6　Hydrogen engine generation set

4.4　Demonstration facility for hydrogen engine generation set

With the aim of assessing/verifying the performance, reliability and safety of a full-scale hydrogen engine generator set, a demonstration facility was newly built at our Sagamihara Plant (4), (5). This facility mainly consists of a hydrogen supply facility (trailer) and a hydrogen engine generator set. The hydrogen pipeline in between was laid above ground. Hydrogen fuel, which is procured through Tomoe Shokai Co., Ltd. from Yamanashi Hydrogen Company Inc., is a green hydrogen called "HyGI." It is produced by water electrolysis using renewable electricity at the Komekurayama P2G Demo Site (Kofu City, Yamanashi Prefecture, Japan). Carbon credits are also applied for CO_2 emissions from hydrogen transportation by trailer truck from Kofu City. Using green hydrogen, we have set up a framework for demonstration testing, based on which the utilization of hydrogen can achieve carbon neutrality throughout the hydrogen supply chain from production to storage to transportation to consumption.

4.5　Trial run of hydrogen engine generation set

The demonstration test using hydrogen as a fuel started in October 2024. While ensuring safety through tests such as hydrogen leak check and protection system function test, the demonstration test has completed the following two operational phases: (1) engine start and (2) verification of stable combustion in the range of up to the rated output (435 kW) (6).

(1)　Engine start

Our 100% hydrogen engine has been designed to be operable solely on hydrogen without needing other fuels, even during start-up. **Figure 7** shows an example of the starting behavior of the engine. After an electric starter is used to rotate the engine at ≈100 min^{-1}, the speed needs to be ramped up to the rated level, while hydrogen is supplied and burnt in a stable manner. In the case of starting the engine whose pipes have been purged with nitrogen, hydrogen has to be combusted without causing abnormal combustion despite the transient deviation caused by some nitrogen mixed in the fuel. It has been confirmed that stable engine start-up is possible by optimizing the sequence parameters of the relevant auxiliary equipment as well as the engine control parameters.

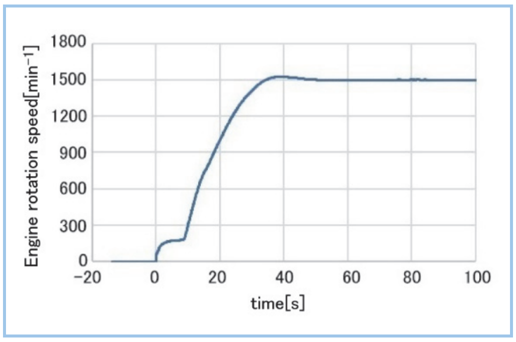

Figure 7　Engine starting behavior

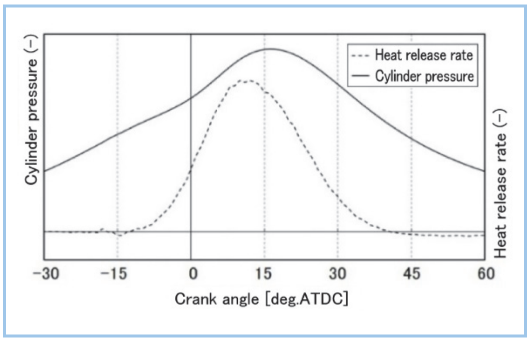

Figure 8　Cylinder internal pressure and rate of heat generation at rated output

(2) Verification of stable operation range

The completion of the start-up test was followed by a trial run under load. As 100% hydrogen engines are prone to backfire, pre-ignition and knocking, it is necessary to operate under conditions in which such abnormal combustion can be avoided. In this testing, the output was increased by 10% at a time to identify the conditions under which abnormal combustion can occur. **Figure 8** shows the cylinder pressure and rate of heat release at rated output. Through this testing, the factors such as air excess ratio, ignition timing, fuel injection timing, and fuel gas supply pressure were optimized for each output level, which has enabled the determination of stable operation conditions in the range from no-load to rated output without abnormal combustion.

5. Conclusion

Toward achieving a low-carbon or carbon-neutral society, MHIET is focusing on the development of hydrogen-fired reciprocating engines. Whether using hydrogen as a fuel or co-fuel, both types of engines, which we are working on and are reported herein, are based on the GSR gas engine series with a sufficient proven record. Our hydrogen co-firing engine products are continuously operable on the city gas 13A with a 15 vol% blend of hydrogen. In regard to 100% hydrogen firing, a demonstration facility using a hydrogen engine generation set was built at our Sagamihara Plant. Now that MHIET is capable of going through the development cycle from planning to design to production to demonstration at its plant, the demonstration test results can be promptly applied to the final product. At this point in time, it has been confirmed that stable operation is possible from engine start-up to power generation at a rated output (435 kW). Our next plan is to assess/verify the reliability. The assessment of the safety required of a power generation set and the performance verification will also be conducted.

We will continue to help achieve a low-carbon or carbon-neutral society by enabling the expanded use of hydrogen through timely development and commercialization of engines running on hydrogen as a fuel or co-fuel according to the level of infrastructure implementation for hydrogen supply and customer needs.

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