The Further Progressed Gas Engine Co-generation System with World's Highest Efficiency of 41.5%

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A new model high-efficiency gas engine has been developed that achieves a generating efficiency of 41.5 %, the highest in the world for a medium-sized gas engine. This represents a 1.1 % further increase over the 40.4% generating efficiency attained in the previous model. This achievement was made possible by improving combustion efficiency through the optimization of the shape of the combustion chamber, reducing various losses through the optimization of valve timing, and enhancing the performance of the turbocharger, all of which were concomitant with the adoption of a long stroke design. At the same time, development efforts were also focused on making the co-generation system more compact, improving the maintainability of the system, and bolstering the competitiveness of the system as a product.

1. Introduction

In recent years, various studies and researches have been conducted into saving energy concerning the destruction of the environment. In particular, research and development activities into the reduction of CO_2 emissions have accelerated with the coming into effect of the Kyoto Protocol since February 2005.

Co-generation systems using natural gas have been highly recognized because of their superiority in high energy efficiency, clean exhaust emissions, and flexible functionality as a distributed power generation that can be used to readily accommodate fluctuations in demand. While demand for such systems can be expected to increase in the future, co-generation systems seem to have been installed already for most users with a large demand for heat in the form of hot water and steam. Consequently, it has become crucial that co-generation systems with high generating efficiency also be developed that can accommodate users who need more electricity than heat.

Mitsubishi Heavy Industries, Ltd. (MHI) and Osaka Gas Company, Ltd. have been jointly developing a gas engine with higher efficiency. In the year 2000, MHI developed a series of gas engines known as the GSR Miller cycle gas engine series (hereinafter referred to as the GSR-M series) in which the Miller cycle was applied to a lean burn gas engine with pre-chamber, achieving a generating efficiency of 40 % for the first time in the world. In 2002, MHI then developed the GSR Advanced Miller Cycle gas engine series (hereinafter referred to as the Advanced GSR-M series) as a new type of gas engine by applying even higher generating efficiency and higher power generation output capabilities to the GSR-M series engine, thereby providing a line up of different engine types with generating efficiency ranging from 40.4 to 40.8 %, the highest thermal efficiency medium-sized engines in the world with a power output of 1 MW or less. MHI has already delivered more than one hundred engine systems, including GSR-M series and Advanced GSR-M series engines, to date, and established a good reputation among customers. Both MHI and Osaka Gas Co., Ltd. are still making every effort to develop gas engines with even higher levels of efficiency.

An overview is presented in this report of the GS6R2 Miller cycle gas engine (hereinafter referred to as the GS6R2-M engine), developed as part of a joint project with Osaka Gas Co., Ltd. and which has achieved the world's highest generating efficiency of 41.5 % as a medium-sized engine, as well as the development of a co-generation system using this engine.

2. Environmentally friendly gas engine co-generation system

2.1 Characteristics of natural gas and gas engines

Gas engines mainly use natural gas and city gas (12A and 13A) as fuels for operation. Methane (CH_4) is the principal component of natural gas and city gas. Compared with other fossil fuels, the ratio of hydrogen atoms (H) to carbon atoms (C) is high at four to one. As a result, water comprises a large proportion of the byproducts produced during combustion, while carbon dioxide (CO_2), which is a major cause of global warming, is generated just a little. Methane has the highest ratio of hydrogen to carbon atoms of all fossil fuels, being 2.7 times greater than that for propane (C_3H_8), 2.3 times that for gasoline (C_8H_{18}), and 1.9 times that for diesel oil ($C_{16}H_{30}$).

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This has a significant effect in reducing CO_2 formation when used as fuel. In addition, natural gas is a low polluting fuel and does not contain any sulfur. Its use does not result in the generation of sulfur oxides (SOx), which cause acid rain, and the emission of particulate matter (PM), which can be detrimental to human health. Moreover, emissions of nitrogen oxides (NOx), which are harmful to the human body, are restrained to low levels, as well.

2.2 The Effective use of energy through co-generation

Co-generation consists of the production of multiple forms of energy such as electricity and heat from a single energy source such as natural gas. It is a system that significantly reduces the wasting of energy as much as possible. The resulting increase in energy efficiency serves to help effectively limit the emission of greenhouse gases as represented by CO_2. At the same time, economic benefits can be realized through the reduction of the energy costs.

3. Technical development of the engine

3.1 Main specifications of the engine

Fig. 1 shows the external appearance of a GS6R2-M engine. **Table 1** shows the main specifications of the GS6R2-M engine together with the GS6R-M engine, which is the 6-cylinder model of the same type, and the Advanced GS6R-M engine. A special feature of the newer gas engine compared with the GSR-M series is the lengthening of the stroke from 180 mm to 220 mm. As a result of this and other enhancements described below, this enhanced gas engine has generating efficiency of 41.5%, thereby achieving the highest level of efficiency for a medium-sized gas engine in the world. Because engine displacement was increased along with the adoption of the long stroke design, the power output increased sharply from 305 kW to 380 kW, compared with an inline 6-cylinder engine with the same brake mean effective pressure (Pme).

Fig. 2 shows the relationship between the power generation output and generating efficiency of a typical gas engine. From the figure it can be understood that the GS6R2-M engine has higher generating efficiency than other gas engines of the same class, even among the high efficiency gas engines that have entered the market recently.

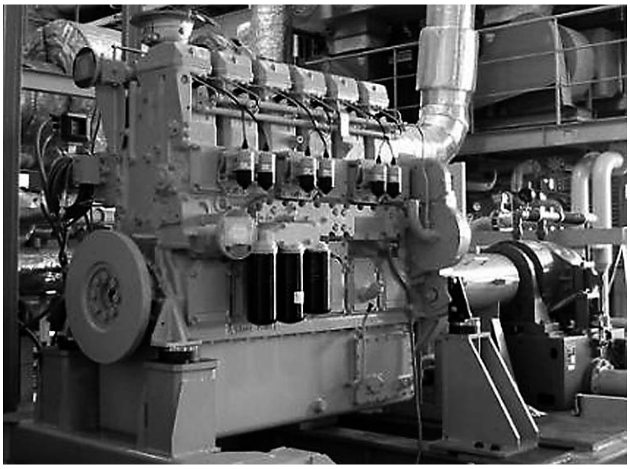


Fig. 1 External view of GS6R2 Miller cycle gas engine
Prototype engine installed at the Osaka Gas Company. Joint performance tests and endurance tests were carried out on the engine.

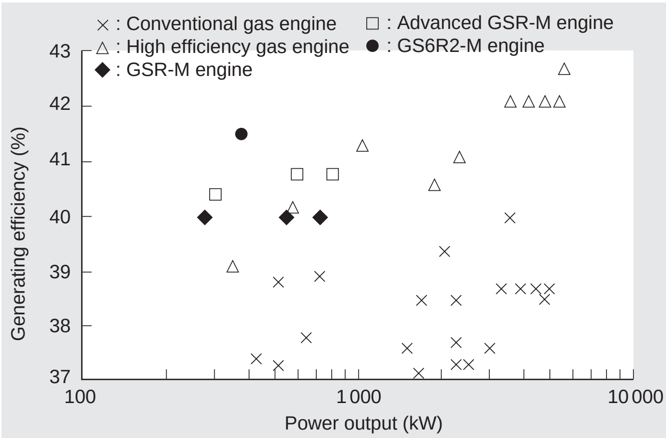


Fig. 2 Relation between generating efficiency and power output in the gas engine
The GS6R2-M engine has the highest generating efficiency in the world among medium-sized gas engines

Table 1 Comparison of Principal Engine Specifications

	GS6R-M engine	Advanced GS6R-M engine	GS6R2-M engine
Engine Specifications	Inline 6 cylinder	Inline 6 cylinder	Inline 6 cylinder
Bore (mm)	170	170	170
Stroke (mm)	180	180	220
Engine displacement (L)	24.5	24.5	30.0
Engine speed (RPM) (min^{-1})	1 200	1 200	1 200
Method of firing	SI w/Pre-chamber	SI w/Pre-chamber	SI w/Pre-chamber
Pme (BMEP) (MPa)	1.20	1.32	1.32
Power generation output (kW)	280	305	380
Thermal output (kW)	241	252	330
Generating efficiency (%)	40.0	40.4	41.5
Total efficiency (%)	74.4	73.8	77.6
NOx (O_2=0%) (ppm)	150 or less (After simplified denitration)		

3.2 The Miller cycle

The Miller cycle is combustion cycle based on the Otto cycle in which the expansion ratio is larger than the compression ratio. **Fig. 3** shows a conceptual diagram of the Miller cycle. Usually, the actual compression ratio can be reduced while the geometrical compression ratio (= expansion ratio) is kept high by shifting the closing timing of the inlet valve forward or backward slightly. (Generally, the inlet valve is closed in the vicinity of the piston bottom dead center during the intake stroke.) This affects the high efficiency of the engine, because the difference in the work units of the expansion stroke and compression stroke becomes greater. In addition, it is also a very effective way of preventing abnormal combustion known as knocking, which occurs when the compression ratio is increased in a premixed combustion engine such as spark-ignited gas engine. This technology has come to be widely adopted in recent high-performance gas engines.

3.3 High increase in efficiency through adoption of a long stroke design

As mentioned in section 3.1, the introduction of a long-stroke design has made it possible to increase the power output of the new engine as a result of the increase in engine displacement compared with the Advanced GS6R-M engine. On the other hand, it is thought that since the Pme of both engines is the same, there is no significant difference in the amount of frictional loss due to each part in the main body of the two engines. In other words, the GS6R2-M engine with its long stroke design has a comparatively low percentage of friction loss to power output. This makes it easier to get higher power from the engine and hence is advantageous in realizing higher thermal efficiency. In addition, since the dead volume inside the combustion chamber is almost equal to that of the GS6R-M engine, the proportion of that is reduced due to the increase in cylinder volume, and the emission of unburnt gas can be kept low. Hence, the long stroke design contributes significantly to the improvement of generating efficiency and low gas emissions.

3.4 Optimization of combustion chamber configuration

Because cylinder volume increases with the adoption of a longer stroke, the combustion chamber configuration needs to be optimized with the same compression ratio as in GSR-M series. Since the configuration of the combustion chamber has a major impact on combustion in a gas engine, it had to be carefully optimized in the GS6R2-M engine. Extensive performance tests were conducted on several different combustion chamber configurations. The cylinder pressure waveforms and related data were then analyzed to get a better understanding of the changes in efficiency in order to find the optimum combustion chamber configuration. This has made it possible to improve the degree of constant volume, which is an indicator of combustion efficiency, and to reduce the amount of unburnt gas, thereby enhancing generating efficiency. **Fig. 4** shows the heat release rates for the GS6R-M engine and GS6R2-M engine. It can be seen from the figure that the heat release ends quickly in the GS6R2-M engine and that this engine has a high degree of constant volume.

3.5 Optimization of inlet valve lift and valve timing

The adoption of the long stroke design has also resulted in an increase in the amount of air-fuel mixture that needs to be supplied to the engine cylinders. As a result the intake valve opening time area with respect to the volume of the air-fuel mixture to be supplied became insufficient and the pump loss increased, thus compelling measures to address these problems. Since the cylinder bore and the structure of the cylinder head are the same as those in the GSR-M series, it is difficult to increase the diameter or to change the configuration of the inlet valve. This problem was handled by comparing the cam lift on the intake valve with that of the GSR-M series and then using a larger cam lift, with the aim of ensuring the volume of the air-fuel mixture supply and reducing pump loss. At the same time, the timing of inlet valve closing was also changed to get optimum Miller cycle.

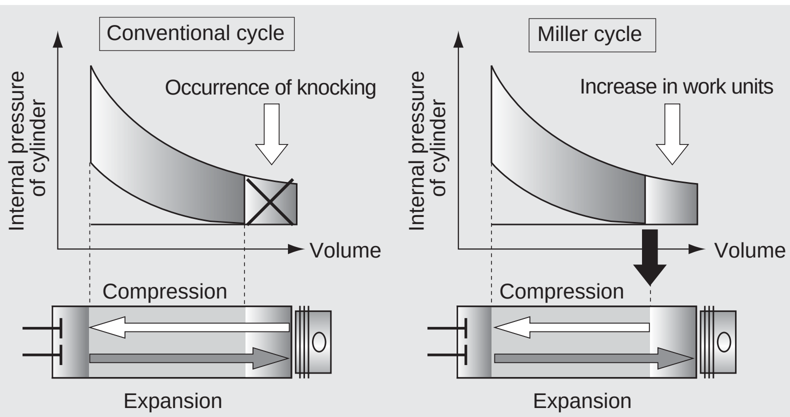


Fig. 3 Concept of the Miller cycle
The expansion stroke is lengthened by the compression stroke that makes it possible to recover more combustion energy while preventing knocking.

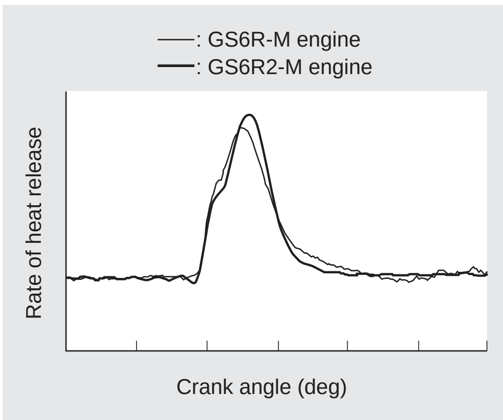


Fig. 4 Comparison of heat release rates
The GS6R2-M engine has a shorter and more efficient combustion period.

3.6 Development of a high-performance turbocharger

In order to handle the increase of the air-fuel mixture volume mentioned in section 3.5, a turbocharger with higher efficiency became necessary to supply enough air-fuel mixture under a higher boost pressure. Thus, a high-performance turbocharger was developed that has stable pressure-charging characteristics and is highly efficient even under a high-pressure ratio. This was accomplished through the introduction of new technology in the turbocharger compressor and turbine parts for the GS6R2-M engine.

The 62 % efficiency of this turbocharger represents a 2 % improvement over previous systems. In addition, the turbine nozzle was optimized, and compatibility between engine performance and operational stability under any condition was achieved.

3.7 Development of highly durable parts

Although the GS6R2-M engine has the same Pme as the Advanced GS6R-M engine, the input heating value of the GS6R2-M engine increases more as the power output increases, placing an intense thermal load on each engine part. As a result, each part needs to have a greater durability. Measures were taken mainly on increasing cooling capability especially for the cylinder heads and pistons, which need to be durable.

Thus, actual temperature measurements were taken for both parts, and it was verified that the temperature of both parts were effectively lowered by several degrees compared with the original parts. Continuous endurance tests exceeding 8 000 hours were conducted by a prototype engine in which both parts were installed. The parts were then disassembled and carefully examined after testing. It was thus confirmed that the durability of the cylinder heads, pistons, and other parts did not show any problems whatsoever.

4. Gas engine co-generation system

4.1 Packaged as a system

MHI provides a complete co-generation system including a gas engine generator set and auxiliary unit as an integrated package. The gas engine generator set consists of a gas engine, generator, battery for starter, lubricating oil tank, generator control panel, gas valve equipment, gas compressor, and other necessary parts that are set up in an enclosure. In addition, the auxiliary unit consists of an exhaust gas steam boiler or hot water boiler, heat exchanger, silencer (muffler), cooling water circulating pump, de-NOx system, de-NOx catalyst, and related equipment which is installed on a common base.

Careful consideration is given to achieving both a compact structure while at the same time ensuring ease of maintenance in the design of the GS6R2-M engine co-generation system package.

4.2 Compact structure of system

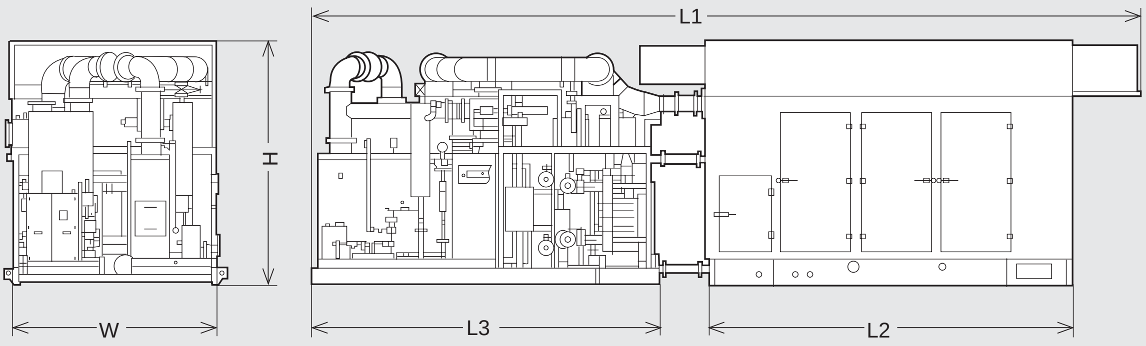
The GS6R2-M engine is taller than the advanced GS6R-M engine due to the longer cylinder stroke. Moreover, the overall dimensions of the generator are larger due to the increased power output of the engine. However, the GS6R2-M engine co-generation system has been kept to a height of 3 300 mm, which is the same height as the existing system, so that the entire unit can be transported on a low height trailer track when the system is delivered to a customer site. Accordingly, disassembly and reassembly of the upper duct need not be done, thereby making it possible to cut on site construction time and costs. Since the generator used in the GS6R2-M engine this time is larger in size, GD^2 is increased. This, in turn, contributes to an improvement in dynamic characteristics, such as transient load change. Therefore, it results in significant benefits for the entire system as well as to the increased efficiency of the generator itself.

On the other hand, since the amount of heat to be recovered increases as power output increases, the various equipment comprising the auxiliary unit, such as the boiler, were upgraded to a higher capacity grade in order to better accommodate the greater heat generated by the system. However, it was possible to arrange all the auxiliary equipment as a single unit that would fit on the same size common base as that used for the previous system by optimizing the piping to each piece of auxiliary equipment and reviewing the piping routes. Although the engine, generator and auxiliary system are all greater in size, the overall dimensions of the system as a whole is not changed at all, and the increase in weight is minimized. **Fig. 5** shows a external view of the system and a comparison of its dimensions with other system.

4.3 Consideration of Maintainability

Usually, once a co-generation system has been installed at a user's site, it will be used for several tens of thousands of hours over more than ten years. Therefore, it is essential that regular maintenance service be provided to maintain the performance and reliability of the equipment. Servicing will range from relatively light maintenance of replacing consumable supplies, such as ignition plugs and lubricant, as well as applying grease to the generator, to more major maintenance including replacement of the cylinder heads and pistons.

Since most overhaul operations are normally carried out on site, and different from automobile engines, a compact enclosed space may put more stress on the service engineer who would need to spend more time and effort to work in such an enclosure of limited space. To solve this problem for the GS6R2-M co-generation system, the arrangement of the components within the enclosure reflects the views of the maintenance department and users in order to reduce the man-hours needed for maintenance work.



Specifications	Position	Dimensions (m)					Mass (power generation set)		Mass (auxiliary machinery unit)	
		L1	L2	L3	H	W	WET (t)	DRY (t)	WET (t)	DRY (t)
GS6R2-M engine	Hot water	10.4	5.0	3.8	3.3	2.8	17.0	16.4	7.9	7.4
	Hot water + steam	11.4	5.0	4.8	3.3	2.8	17.0	16.4	9.4	8.9
Advanced GS6R-M engine	Hot water	10.4	5.0	3.8	3.3	2.8	15.6	15.0	7.0	6.5
	Hot water + steam	11.8	5.0	4.8	3.3	2.8	15.6	15.0	9.0	8.5

Fig. 5 External view and dimensions of co-generation system
A characteristic of this engine system is that it has the same external view and dimensions as previous systems. Increases in weight due to greater system capacity were kept to a minimum, as well.

5. Conclusion

The GS6R2 Miller cycle gas engine was jointly developed by MHI and Osaka Gas Company, Ltd. using the analytical and evaluation technologies of both companies. This engine has achieved a generating efficiency of 41.5 %, the best rating for medium-sized gas engines of this type in the world. Commercial sales of the engine were launched in April 2005. Both companies are continuing efforts to develop engines with even better generating efficiency and reliability, including enhanced durability, in the future by improving the combustion and other characteristics of the system.

A compact structure and ease of maintenance were major goals in the design of the co-generation system using the GS6R2-M engine from the beginning. As a result, a GS6R2-M engine can be installed in the same space as an advanced GS6R-M engine. Moreover, lower running costs are also achieved at the same time by saving the number of man-hours needed to maintain the system. MHI is continuing to develop new co-generation systems to meet the demands of the market by improving cost efficiencies even further, for example simplifying the system as a whole and integrating several controllers.

MHI fully intends to continue developing high performance and low emission engines and co-generation systems that enable users to reduce CO_2 emissions, save energy costs, and contribute to society now and in the future.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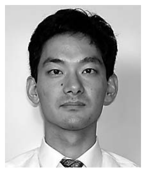
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