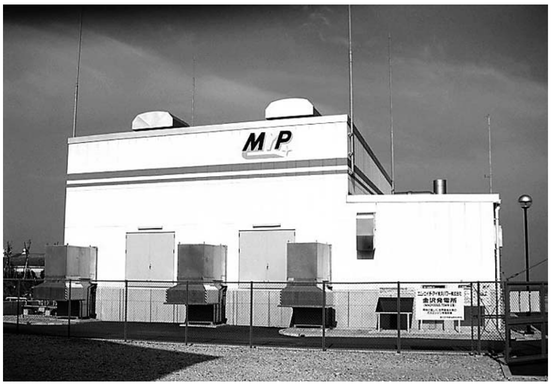


MITSUBISHI Lean-burn Gas Engine with World's Highest Thermal Efficiency

AKIRA TSUNODA
HIROMI SHIMODA
TATSUO TAKAISHI

Mitsubishi Heavy Industries, Ltd. (MHI) manufactures low NOx lean-burn gas engines in a wide output range from small output "GSR" to large output "MACH-30G". MACH-30G is featured a micro pilot with powerful ignition energy replacing spark plugs at an output of 3 650 to 5 750 kW, and GSR has a compact package featuring a Miller cycle, covering an output range of 280 to 845 kW. Each engine has achieved the world's highest electrical efficiency of 44% and 40%, respectively, in each output range. At present, more than 20 sets of each model are in service, and their high performance and reliability are highly evaluated.

1. Introduction

1.1 History of development of high-efficiency gas engine

Under the background of increasing need for lower CO_2 emission recently, in the field of power generation engines there is an increasing demand for gas engines featuring low emission of harmful constituents such as CO_2, NOx and particles. Accordingly, MHI has developed low NOx lean-burn gas engines by introducing the latest technologies in order to achieve the world's highest electrical efficiency. MHI has already succeeded in delivering gas engines with the highest thermal efficiency in the world, namely, MACH-30G with pilot ignition system using a little fuel oil as ignition source in the 5 000 kW class, and GSR using the Miller cycle in the under 1 000 kW class, and is receiving good reputations.

1.2 Lineup of MHI gas engines

Table 1 shows specifications in comparison with those of conventional engines. MACH-30G has its brake mean effective pressure (BMEP) raised from 13 bars to 20 bars, the equivalent level of a diesel engine, and has also been improved in its electrical efficiency from the conventional 39.3% to 44.0% by the introduction of a pilot ignition system and combustion control system. The appearance of MACH-30G plant is shown in **Fig. 1**.

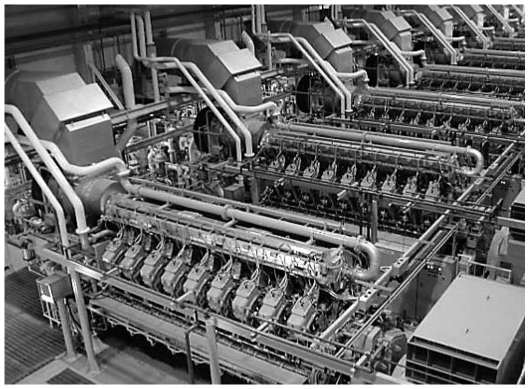


Fig. 1 Appearance of MACH-30G
Appearance of MACH-30G installed at a plant in Japan.

Table 1 Specifications of MHI gas engines

	MACH-30G		GSR	
	Conventional type	Pilot ignition	Conventional type	Miller cycle
Generator output (kW)	2 400 – 3 750	3 650 – 5 750	320 – 1 015	280 – 845
Cylinder bore/stroke (mm)	300/380	300/380	170/180	170/180
Speed (rpm)	720/750	720/750	1 500/1 800	1 200/1 500
BMEP (bar)	13	20	11	12
Electrical efficiency (%)	39.3	44.0/42.5	35	40
NOx (ppm, O_2 = 0%)	200	200/100	150	150 (with de-NOx system)
Features	Lean-burn with pre-combustion chamber	Pilot ignition	Lean-burn with pre-combustion chamber	Miller cycle
	Spark ignition		Spark ignition	

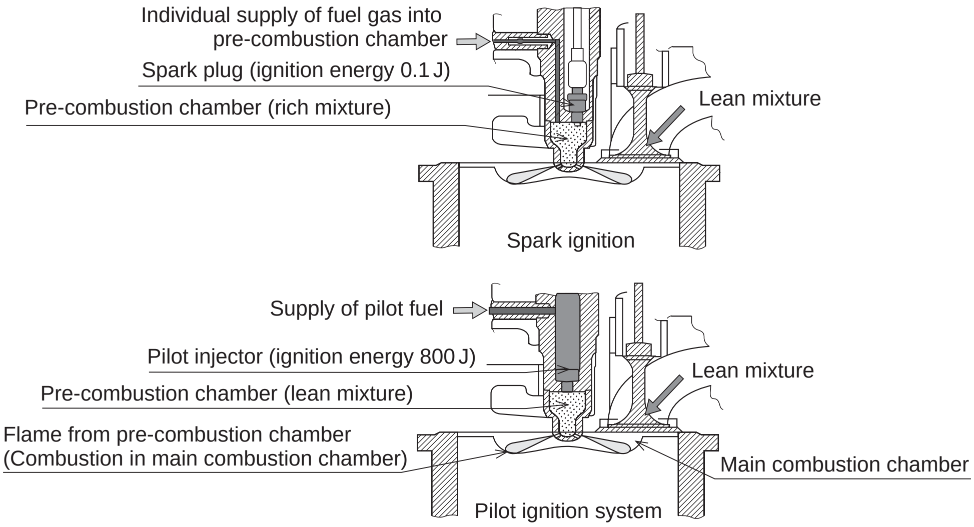


Fig. 2 Comparison of pilot ignition system and spark ignition
Instead of conventional spark ignition, MACH-30G uses the pilot ignition system whose ignition energy is 8 000 times higher.

GSR gas engine features improved electrical efficiency from 35% of conventional engines to 40%, thanks to an expansion ratio and introduction of a Miller cycle that enhances the cycle efficiency with a high-efficiency turbocharger.

With MACH-30G and GSR, MHI offers gas engines of highest efficiency in a wide range from small to large output.

2. Features of MACH-30G

The features of MACH-30G are shown below.

2.1 Pilot ignition system

Fig. 2 shows the features of the pilot ignition system in comparison with conventional spark ignition. Instead of ignition using conventional spark plugs, the pilot ignition system features ignition of gas in a pre-combustion chamber by injecting (1% or less in calorific ratio) a little fuel oil from a pilot injector. The pilot fuel is very small in quantity but has a powerful ignition energy roughly 8 000 times that of a spark plug, so that combustion is stable and efficiency is improved. Moreover, owing to the potent ignition energy, there is no need to prepare a high-concentration air-fuel mixture in the pre-combustion chamber as required in spark ignition engines, and production of NOx in the pre-combustion engine is lowered. As a consequence quite low NOx of 100 ppm (O_2 = 0%) has been realized for the first time in the industry, which is less than half the emission by other manufacturers, and local regulations can be met without installing a de-NOx system.

The maintenance interval of a fuel injection valve for pilot ignition is 4 000 hours, which is more than double compared with 1 000 to 2 000 hours for ignition plugs, . In addition, by using powerful ignition energy, the system can stably burn various low calorie gases such as bio gas and pyrolysis gas.

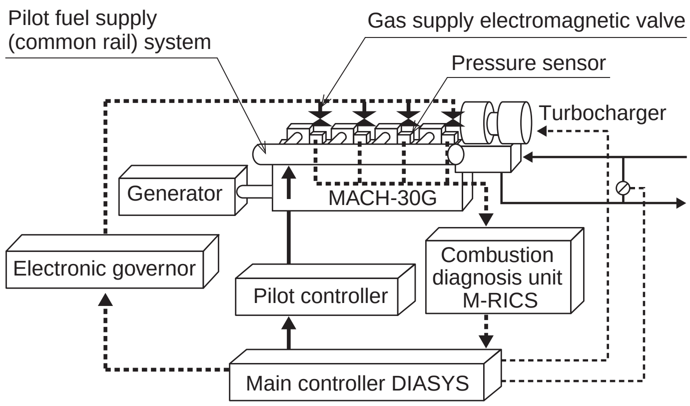


Fig. 3 Electronic fuel supply system and combustion diagnosis system M-RICS
M-RICS optimizes control of combustion state of engine at all times by using main controller DIASYS.

2.2 Combustion control system M-RICS (Mitsubishi Real-time Intelligent Control System)

Fig. 3 shows M-RICS (a registered trademark of MHI), a combustion control system using electronic fuel supply system and combustion diagnosis unit of MACH-30G. In M-RICS, the combustion condition is diagnosed in nine ranks depending on the combustion pressure obtained by directly sensing with a cylinder pressure sensor installed in each cylinder, and the combustion is controlled by automatically adjusting the volumes of pilot fuel and fuel gas and the timing individually in each cylinder by means of a main controller, DIASYS (a registered trademark of MHI). As compared with conventional vibration-type knock sensors, each cycle can be controlled at a high response by means of a solenoid operated pilot fuel injector using a common rail system and gas admission valve, realizing the following features (patent pending).

(1) Improved efficiency by balancing combustion in all

cylinders

The pilot ignition timing can be adjusted automatically on the basis of the diagnosis result of combustion pressure, and the combustion of each cylinder can be balanced all the time. As a result, all cylinders operate at maximum efficiency, which greatly improves thermal efficiency.

(2) Optimum control against calorific fluctuations

M-RICS diagnoses and controls the firing pressure itself optimally in spite of calorific fluctuations of the fuel or aging of components. Accordingly, optimum combustion is always adjusted automatically and high efficiency is maintained for a long period. At present, a plant using four types of LNG with different calorific values is operating steadily.

(3) Avoidance of abnormal combustion

Fig. 4 compares the cylinder pressure trace from M-RICS in knocking and single of vibration-type knock sensor of other manufacturers. Since M-RICS senses the cylinder pressure directly, abnormal combustion can be diagnosed with high precision, the injection timing and amount of pilot fuel are controlled, and abnormal combustion is eliminated. It also has an automatically fuel cut system "capable of continuing power generation without stopping engine in case of unexpected trouble" which is important in an engine for power generation, therefore any accident can be avoided with ample allowance.

(4) Preventive maintenance function by diagnosis of abnormality

In the remote monitoring system of MACH-30G, combustion control data of M-RICS is monitored at the remote monitoring center. As compared with conventional diagnosis of abnormality by temperature or pressure level, a more precise and prompt diagnosis of abnormality is possible, and preventive maintenance functions will be reinforced henceforth.

2.3 Production and order books

Table 2 shows order books and deliveries of MACH-30G. A total of 19 sets in five plants were ordered in 2001, and the first and second sets were put into commercial operation in October 2002 at MHI Yokohama Power (MYP) in MHI Yokohama Dockyard & Machinery Works. An overview of MYP is shown in the title photo-

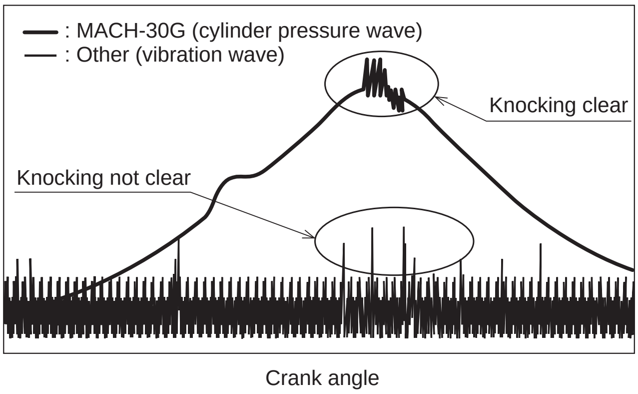


Fig. 4 Comparison of cylinder pressure wave and vibration wave in knocking
Cylinder pressure wave can detect the combustion state more accurately than the vibration value.

graph. As of March 2003, all 19 sets have been committed and are running steadily. A further 16 sets for 11 plants were ordered including overseas, and the total of order books is 35 sets.

2.4 Future outlook of MACH-30G

(1) Improvement of electrical efficiency

In MACH-30G, tests for further improvement of electrical efficiency are being conducted, including the Miller cycle already developed in GSR.

(2) Improvement of total efficiency

To create advantages for steam consuming customers, a duct burner capable of generating 2.5 times more steam than conventional has been developed with MHI's original boiler technology. It is named MACH-DUET (MACH Duct burner for Utility Efficient Technology), and its verification test has been successfully completed.

(3) Remote operation

Remote monitoring system of the standard equipment has been further extended to remote operation to enable operation control from a remote station. Its system development has already been completed, tests with prototype are being planned, and customers' needs will soon be satisfied.

3. Cogeneration package by Miller cycle gas engine

3.1 GSR Miller cycle gas engine

GSR Miller cycle gas engine has been developed for the purpose of attaining electrical efficiency equivalent to that of a diesel engine, on the basis of the GSR lean-

Table 2 Delivery of MACH-30G

	2000	2001	2002	2003	Running hours (h)
Prototype (6 cylinders): 1set	■	■	■	■	Approx. 8 000
MHI Yokohama Power: 2sets			■	■	Approx. 5 000
Japan: 7sets			■	■	Approx. 4 000
Other plants in Japan: 10sets				■	Approx. 2 000

Orders received in 2001: 19 sets in 5 plants in Japan
Orders received in 2002: 15 sets in 10 plants in Japan, 1set in 1 plant overseas
(Note) Running time is cumulative time as of July 2003.

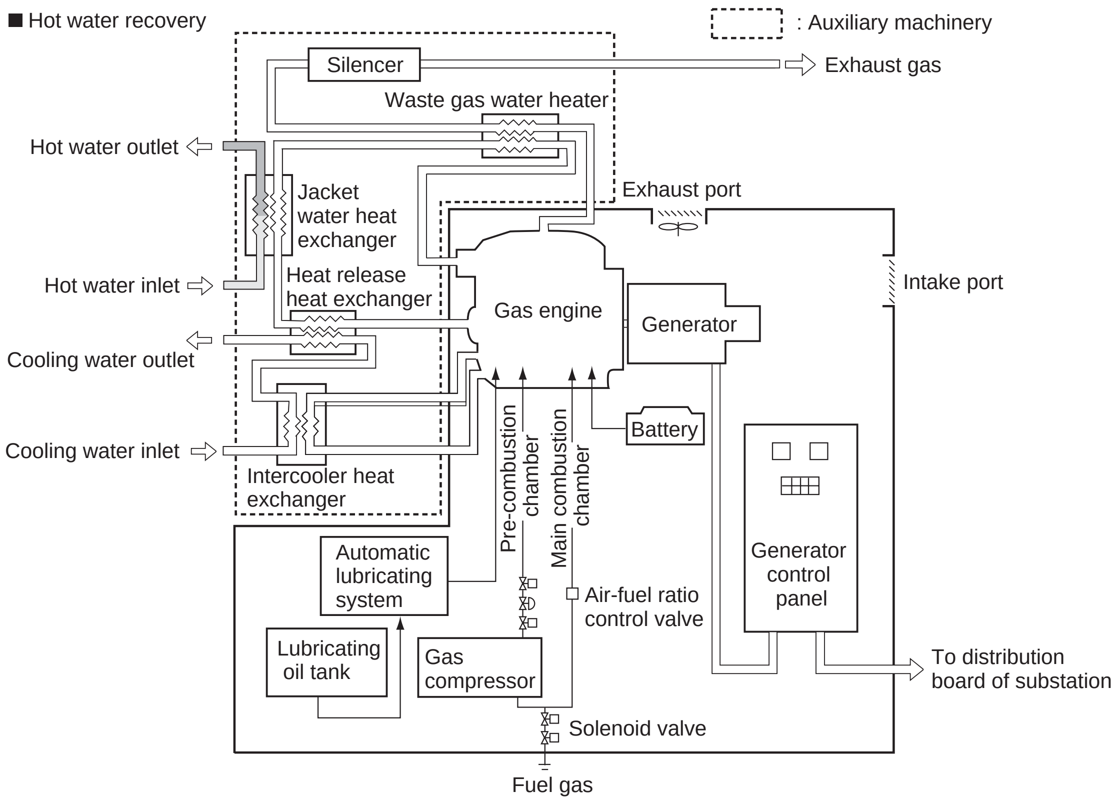


Fig. 5 Block diagram of hot water recovery system
Auxiliary machinery system for recovery of hot water.

burn gas engine noted for its high efficiency and low NOx emission., By increasing the expansion ratio with Miller cycle in combined with improving the efficiency of the turbocharger and optimizing the design of combustion chamber, the world's highest electrical efficiency of 40% in this class has been achieved.

3.2 Cogeneration package

(1) Outline

Miller cycle gas engine generator sets were developed jointly with Osaka Gas Co., Ltd., and products were marketed in April 2001. Total efficiency is similar to that of the ordinary lean-burn gas engine cogeneration package (conventional type), but electrical efficiency is about 5% higher, and this package is favored by customers engaged mainly in supplying electric power. As of March 2003, a total of 19 sets are running, and another 19 sets will be installed by the end of October 2003 including some trial sets at present. An outline of the package is given.

(2) Package

Components of the cogeneration system around the engine include the engine, generator, battery for starting, pump, heat exchanger, silencer, boiler, and gas compressor. The variation is versatile, but customers' specifications can be satisfied promptly by standardizing the components on the basis of the basic system.

The cogeneration system using gas engine is classified into two types: hot water recovery system and hot water + steam recovery system. Accordingly, units are composed in consideration of the common parts and different parts of the two systems, and the unit including the generator (generator set) and the unit including the heat recovery equipment (auxiliary machinery). The auxiliary machinery is offered in two specifications, for the hot water recovery system and the hot water + steam recovery system.

The generator set comprises engine, generator, battery for starting, lubricating oil tank, generator control panel, gas valve equipment, gas compressor, etc. The auxiliary machinery comprises steam boiler or hot water boiler, heat exchanger, silencer, cooling water circulating pump, de-NOx system, de-NOx catalyst, etc. **Fig. 5** is a block diagram of the hot water recovery system and **Fig. 6** is a block diagram of the hot water + steam recovery system.

The standard package was designed in consideration of maintenance and compact structure. Opinions and requests from the maintenance section and customers of conventional machines were also taken into consideration to revise needed parts. By assembling into units simply by connecting the generator set and the auxiliary machinery at the time of installation, the necessary field work consists only of connecting after the secondary stage (cooling water piping system, hot water recovery piping system, steam recovery piping system, drain, etc.), and the term of field work is conspicuously shortened.

The appearance and dimensions of the package are

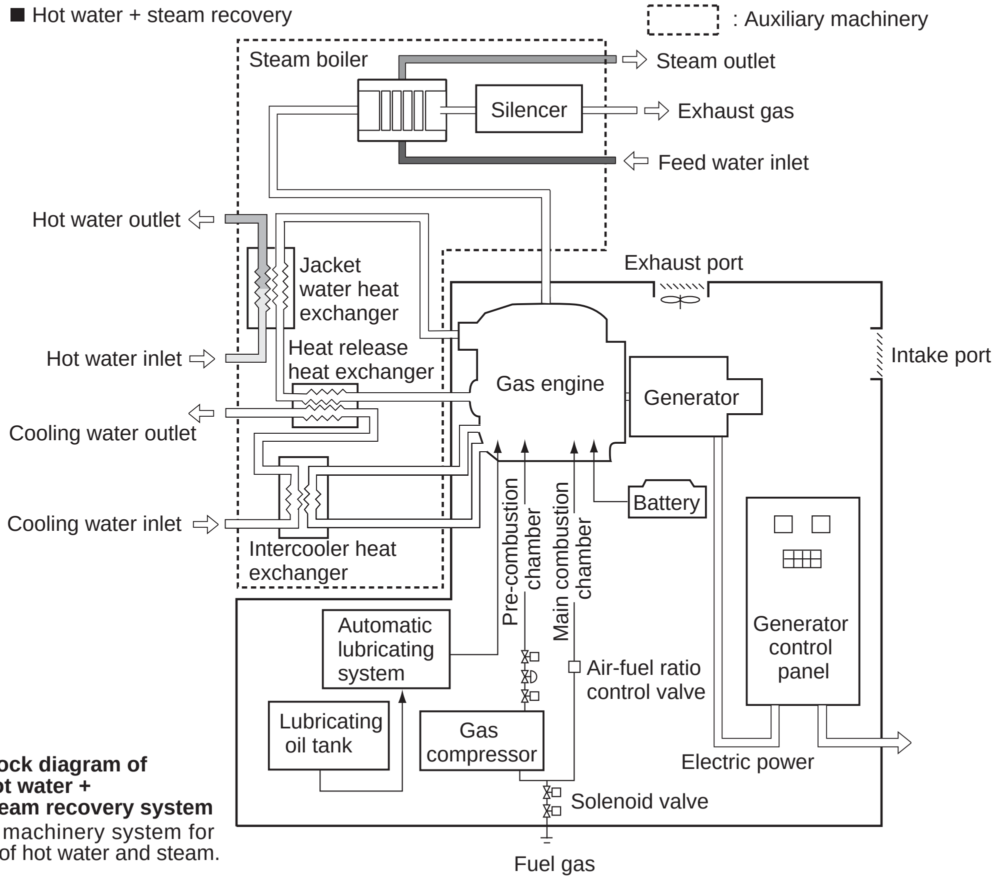


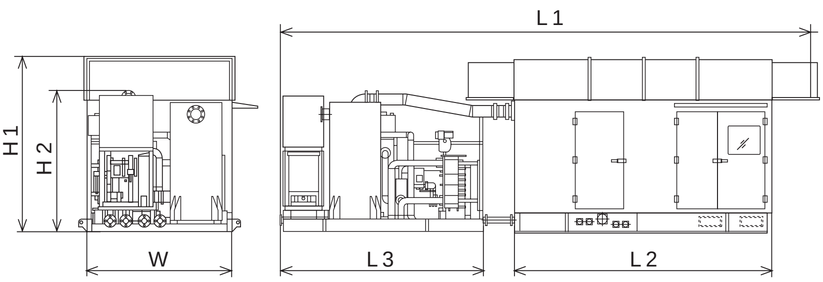
Fig. 6 Block diagram of hot water + steam recovery system
Auxiliary machinery system for recovery of hot water and steam.

shown in **Fig. 7**. **Fig. 8** shows the appearance of an actual GSR package (an example of GS12R Miller cycle 560 kW, hot water recovery system).

(3) Consideration in unit design

Conventional power generation systems are higher than 3 300 mm, and the upper duct portion of the generator set must be cut apart at the time of transportation. In this package, the height of the generator set is not more than 3 300 mm, and the set can be transported intact on a low loading platform car while duct removal and reassembling work are not needed in the field. Accordingly, costs are lower and the term of work is shortened.

With regard to the auxiliary machinery, units for 1 200 min^{-1} (60 Hz) and 1 500 min^{-1} (50 Hz) can be used in common for each engine. The temperature setting of the secondary side of the heat exchanger at the hot water recovery side is determined on the basis of past experience of installation of cogeneration packages, and a wide temperature range is set (83 to 88 ^{o}C, the range required by the absorption chiller and Gen-link). The heat balance varies with environ-



Type	Dimensions, position	Dimensions (m)						Mass (generator set)		Mass (auxiliary machinery)	
		L1	L2	L3	H1	H2	W	WET(t)	DRY(t)	WET(t)	DRY(t)
GS 6 R	Hot water	10.4	5.0	3.8	3.3	2.8	2.8	17.0	16.5	8.0	7.5
	Hot water + steam	11.7	5.0	4.8	3.3	3.9	2.8	17.0	16.5	11.0	10.0
GS12R	Hot water	10.6	5.7	3.2	3.3	4.1	3.0	23.5	22.0	8.0	7.5
	Hot water + steam	12.4	5.7	5.0	3.3	4.3	3.0	23.5	22.0	11.0	10.0
GS16R	Hot water	12.6	6.3	3.5	3.3	4.1	3.0	27.0	25.5	10.0	9.0
	Hot water + steam	13.3	6.3	5.0	3.3	4.4	3.0	27.0	25.5	11.6	11.0

Fig. 7 Appearance and dimensions of package
The package consists of a generator set and auxiliary machine, and is very compact.

Fig. 8 GSR package in operation
Appearance of GS12R operating in hot water recovery system.

ments, and a thermal tolerance of about 15% is set in the heat exchanger.

(4) Future outlook of package

As mentioned above, three engines (GS6R, GS12R, GS16R) were standardized in the generator set, auxiliary machinery for hot water recovery system, and auxiliary machinery for hot water + steam recovery system. Since the package was reviewed in November 2002, new orders have been received - namely, 5 units for GS6R, 6 units for GS12R, and 4 units for GS16R. These units are currently in the process of manufacture or trial run. Further efforts will be made to make a more compact design for auxiliary machinery and to increase output to meet market needs.

4. Conclusion

MACH-30G features a much lower emission level than conventional gas engines, and has notably improved efficiency thanks to the pilot ignition, achieving an electrical efficiency of 44%. The engines are demonstrating stable continuous operation in plants and are highly evaluated by customers.

GSR Miller cycled gas engine cogeneration package has improved efficiency to the 40% level by the Miller cycle. Components are assembled into standard packages, the term of work has been shortened and the cost lowered, and many orders are expected from now on. On the basis of the standard package, optical packages can also be offered at the request of customers.

At present, development efforts are being promoted to present a wide lineup of gas engines by integrating various technologies including the pilot ignition and Miller cycle, and higher efficiency than that of diesel engines is envisaged in a wide range of outputs.

Power generation plants using bio gas and pyrolysis gas are also planned, and MHI is determined to contribute to the global warming.

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YOKOHAMA DOCKYARD & MACHINERY WORKS

Akira Tsunoda

GENERAL MACHINERY & SPECIAL VEHICLE HEADQUARTERS

Hiromi Shimoda

NAGASAKI RESEARCH & DEVELOPMENT CENTER

Tatsuo Takaishi