Approach to High Efficiency Diesel and Gas Engines

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To prevent global warming, the social need to improve the thermal efficiencies of engines and thereby reduce CO_2 emissions is being increasingly acknowledged. As a comprehensive engine manufacturer, Mitsubishi Heavy Industries, Ltd., (MHI) has been working on various technological developments to address the increased demand for dealing with environmental and energy issues regarding clean emission gases and reduced CO_2 output. This paper outlines MHI's approaches to improving the thermal efficiency of small and large diesel and gas engines to enable the clean and effective use of fuel oil and natural gas as valuable human assets.

1. Outline of the development and high-efficiency performance of engines

MHI has developed and currently manufactures piston engines, with the world's widest output, ranging from small gasoline engines (less than 1 kW) to large, low-speed diesel engines (68 MW class). Moreover, MHI is a comprehensive engine manufacturer that produces major components such as exhaust turbochargers and fuel injection systems. These are used in engines for a wide range of products, including vehicles and ships, various mobile industrial machines, and cogeneration and electricity generation equipment. Thus, MHI plays an important role in supporting worldwide economic development.

However, piston engines have encountered environmental and energy problems, such as air pollution caused by exhaust gas and global warming caused by CO_2 emissions. The company is striving to utilize and evolve its wide technological capabilities toward solving these problems, and is working on developing engines that respond to the diverse and sophisticated needs of its customers.

In view of its improved thermal efficiency, which is directly related to reduced CO_2 emissions, a piston engine is inherently advantageous in its working principles and characteristics. In a piston engine, a sequence of strokes, including compression, combustion, and expansion, takes place repeatedly within one cylinder, making up a high-temperature pressure cycle. The maximum temperature constraints of the working media inside the cylinder are not very severe due to the unsteady cyclic combustion. A piston engine has another advantage in that its thermal losses can be reduced because of the slow gas flow, leading to higher thermal efficiencies. This will be discussed below. As a result, the highest thermal efficiencies are realized in small- to medium-sized engines, as shown in **Fig. 1**.

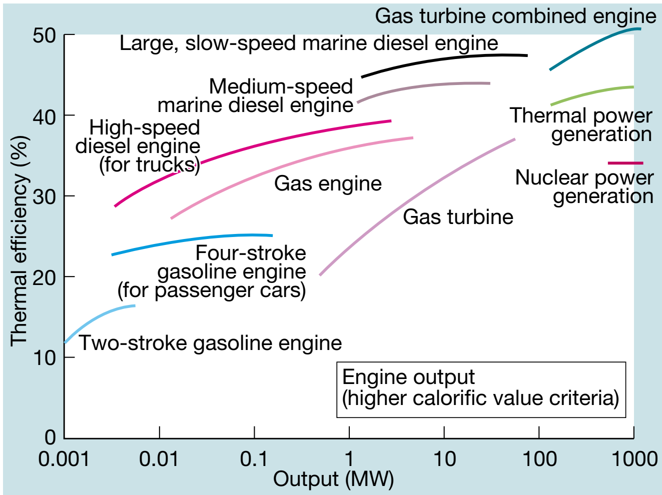

Fig. 1 Thermal efficiencies of various types of small- to medium-sized diesel and gas engines

An outline of the company's efforts toward improving the thermal efficiency of diesel and gas engines is given below.

2. Improving the thermal efficiency of diesel engines

2.1 Four-stroke diesel engines for power generation and industrial use

To respond to the various needs of customers, MHI provides a wide lineup of four-stroke diesel engines, ranging from 5 kW to 15 MW output.[1] The fuels used include a wide range of fuel oil, such as gas oil, kerosene, marine diesel oil, and bunker fuel oil. Partly due to the recent rise in crude oil prices, reductions in specific fuel consumption and improvements in thermal efficiency have become essential technological requirements to reduce running costs in response to the strong demand from customers. To respond

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to the increasing demand for improved thermal efficiency and environmental compatibility, MHI is working on improving the thermal efficiency of its medium-sized diesel engines used for power generation.

In addition to the SU3 and MARK-30B engines, with output ranges of 2.0 to 4.0 MW and 5.2 to 8.1 MW, respectively, an in-line 2.7-MW six-cylinder engine has recently been developed; both its output and thermal efficiency are better than in conventional engines. The SU3 and MARK-30B engines have attained generation efficiencies of 44.1% and 46.8%, respectively, which are better than any other diesel engine in the world in this class. To achieve a high thermal efficiency, the thermal efficiency and output of both of these engines were improved simultaneously by adopting a common design concept that included an increase in the maximum cylinder and fuel injection nozzle pressures, the adoption of a long stroke, and the use of a high-pressure ratio turbocharger. By introducing electric control technology, mainly to the fuel injection system, MHI plans to produce a diesel engine that can satisfy not only the economic needs of its customers, such as a high thermal efficiency and output, but also is compatible with environmental concerns, such as reduced NOx and particulate matter emissions.

For further CO_2 reductions and improvements in thermal efficiency, the combustion performance of the engine itself must be improved and breakthrough technologies are required to reduce the friction loss of various parts, for example, the piston rings, improve the cycle efficiency, and recover the energy lost in the exhaust gas.

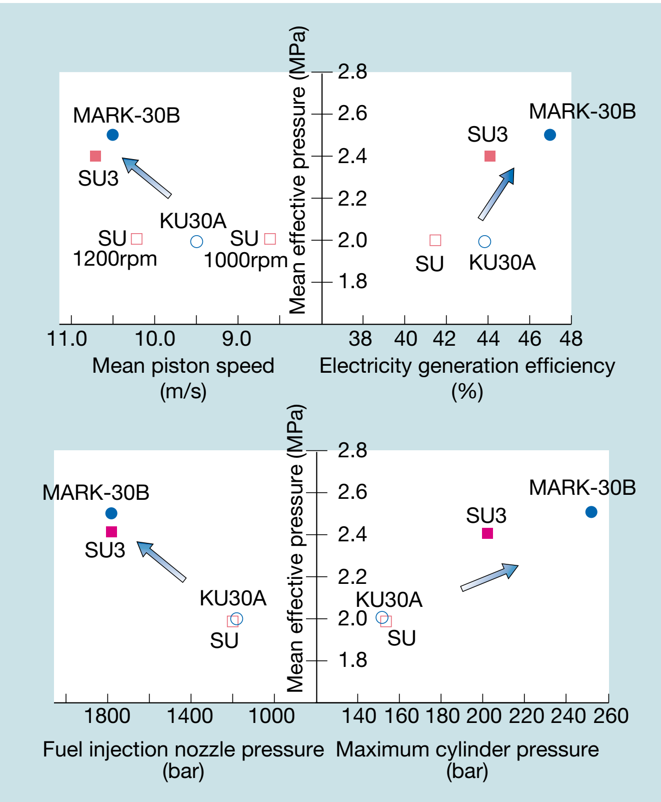

Fig. 2 Typical performance values for conventional engines and the SU3 and MARK-30B engines, including thermal efficiency, mean effective pressure, injection pressure, and maximum cylinder pressure

2.2 Low-speed, two-stroke marine diesel engines

While economic efficiency continues to be an issue (reduced fuel consumption and the use of a relatively inexpensive heavy fuel oil), a strong demand exists for a substantial reduction in the polluting elements of the exhaust gases to protect the global environmental and prevent marine pollution, as well as a reduction in CO_2 emissions to prevent global warming. Various technological developments are currently being pursued to address these challenges.

From their beginning, large, low-speed, two-stroke marine diesel engines have had a high level thermal efficiency of over 50% (lower calorific value criteria), which is higher than in other engines and turbines. This high thermal efficiency is obtained because of the large cylinder diameter, long stroke, high air excess ratio, and low revolution speed. These factors are assumed to contribute to the reduction of various losses and the realization of a cycle that is thermodynamically close to ideal. From the viewpoint of combustion, a slow gas flow inside the cylinder is achieved as static compression and expansion are enabled in the piston engine. Therefore, although the working media reach high temperatures and pressures, the heat loss can be reduced. The temporal constraints of unsteady combustion in low-speed, two-stroke diesel engines are not as severe as in small, high-speed diesel engines. Because of this, the gas flow speed inside the cylinder can be reduced, which is advantageous from the perspective of reducing the heat loss and increasing the thermal efficiency.

Based on this background, MHI has developed the UEC Eco-Engine in response to the need for large, low-speed marine diesel engines by introducing new electronic control technology.[2] The conventional mechanically controlled systems, including the fuel injection, exhaust value, starting, and cylinder lubrication systems, are electronically controlled in this engine so that the operation timing and fuel injection rate can be freely changed according to the engine load, ambient conditions, and fuel properties. As a result, the trade-off relationship between the NOx emissions and fuel consumption rate can be greatly improved, as shown in **Fig. 3**. In comparison with conventional cams, this engine reduces NOx emissions by 10 to 15 % when the NOx priority mode is selected and the fuel oil consumption is kept constant, and improves the fuel oil consumption by 1 to 2% when the fuel oil consumption priority mode is selected and the NOx emissions are kept constant. Thus, MHI can provide marine diesel engines that satisfy the economic efficiency required by customers while being friendly to the global environment.

To attain further CO_2 reductions, additional studies are required to increase the thermal efficiency of the engine itself and to recover the energy lost in the exhaust gas and the waste heat in the exhaust gas and cooling water.

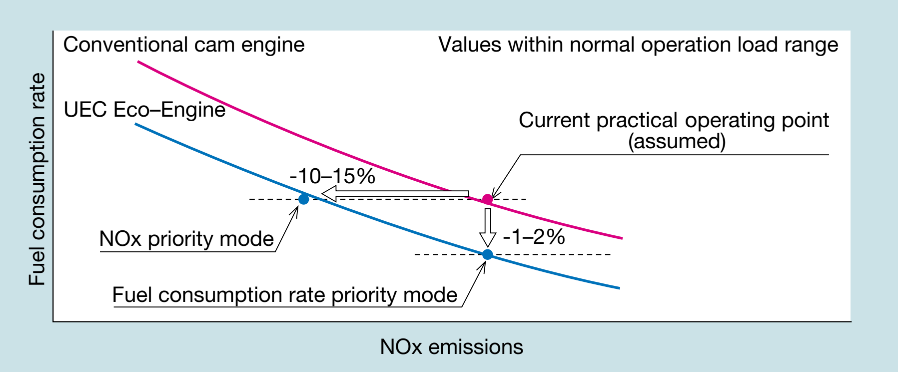

Fig. 3 Relationship between fuel consumption rate and NOx emissions
A comparison of the trade-off relationship between the fuel consumption rate and NOx emissions indicates that an electrically controlled engine is superior to a conventional cam engine.

Since MHI also manufactures exhaust turbochargers, the company is working on developing a hybrid turbocharger.

3. Improving the efficiency of gas engines

Gas engines using natural gas or city gas as fuel produce less exhaust gas emissions containing CO_2, which causes global warming, and other environmentally adverse elements, such as NOx, SOx, and PM. Thus, these are environmentally friendly engines.

MHI manufactures low-NOx, lean-burn gas engines with a wide output range from low-power GSA engines to high-power MACH-30G engines.[3] The GSR engines have a range of 280 to 845 kW, adopt the Miller cycle, and have attained a generating end efficiency of 41.5%, which is the best in the world for this class. The MACH-30G engine has a range of 3,650 to 5,750 kW, and has attained a generating end efficiency of 44.5% by adopting pilot ignition instead of spark plugs and using the Miller cycle.

3.1 High-speed GSR gas engines

MHI was the first company in the world to apply a lean-burn system and the Miller cycle to gas engines with a power generation output of less than 1,000 kW. As shown in **Fig. 4**, the CO_2 emissions were reduced by 12% compared to the company's conventional engines. The CO_2 emissions were equivalent to 75% of those of diesel engines. The power generation of gas engines can satisfy customers requiring a large amount of hot water and steam, and those requiring mainly power generation, who focus on improved generation efficiency while responding to needs for reduced CO_2 emissions.

By continuously aiming to achieve both higher thermal efficiencies and better reliability through further improvements, MHI intends to contribute toward preventing global warming while improving the economic efficiency of its engines.

3.2 Medium-speed MACH-30G gas engine

Large gas engines with an electricity generation output of over 1,000 kW require a lean-burn system that can attain a high thermal efficiency and low NOx emissions. The MACH-30G engine has also achieved stable combustion of a lean mixture by adopting a micro-pilot ignition using an electronically controlled common-rail fuel injection system.

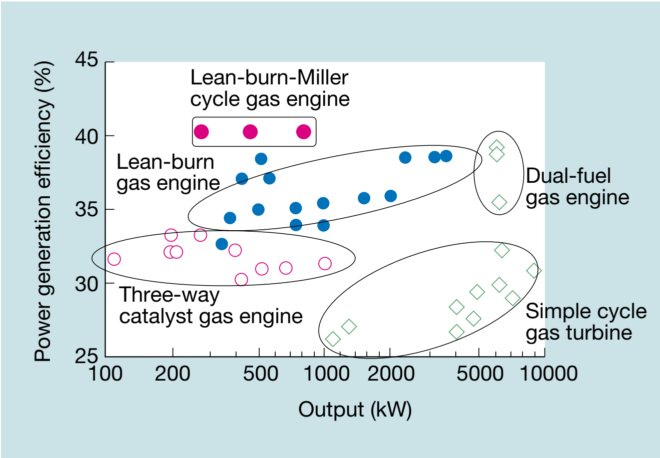

Fig. 4 Improvement in gas turbine efficiency
A power generation efficiency of 40% was achieved by applying the Miller cycle to a lean-burn gas engine, yielding an efficiency higher than that of gas turbines.

In addition to the improved electricity generation efficiency, a total efficiency above 80% was attained, including the recovery of high- and low-temperature water, thus successfully responding to customers' needs.

While continuously working to improve electricity generation efficiency, MHI aims to study the possible application of this engine to power generation plants that use various types of gas, such as biogas and waste product gas, and to thus contribute toward preventing global warming.

4. Conclusions

This paper has described the technological developments of diesel and gas engines that can directly contribute to the reduction of CO_2 emissions to prevent global warming. Based on predictions of continued growth in the world's energy requirements and economic development, more intense and accelerated efforts toward the reduction of

CO_2 emissions are essential. While making the best of the many years of technological knowledge accumulation as an all-around manufacturer of engines, MHI will continue to provide products that can respond to society's requirements by introducing advanced sophisticated technology. Aiming at achieving harmony between the earth's environment and an affluent society, the company will continuously strive to develop engine technology that responds to customers' trust.

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