Development of High Power KU30GA Gas Engine

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We developed a micropilot KU30GA gas engine ignited not by spark plugs but by gas oil less than 1% of total fuel energy. Brake mean effective pressure (BMEP) was increased to 20 bar, which covers output from 3.7MW to 5.8MW with V-12, 14, 16, and 18 cylinder configurations. This engine has been tested with the common rail system for pilot injection, the VG turbocharger for air/fuel ratio control, and knock detection and control system for smooth operation. In this test, we achieved high thermal efficiency of 43.8% and low NOx emission of 0.5 g/kWh.

1. Introduction

In the current situation of strict environmental controls, as alternate fuel for liquid fuel that has been the main energy source until now, attention is turning to gas fuel as the fuel for this century that produces less CO_2 emission and less toxic emissions such as NOx and particulate emission. For industrial applications, demand for gas engines burning gas fuel has been increasing for the past several years even for large lean-burn gas engines that, achieving high efficiency with low NOx emission, are favorably evaluated.

However, in comparison with diesel engines of the same size, conventional gas engines have lower output per piston displacement and higher price per unit output. Therefore, they have been considered less economical than diesel engines. Consequently, as the next generation of engines, a more powerful and efficient gas engine that is economically and environmentally compatible was desirable.

Accordingly, as the successor to the KU30G engine, which is a spark ignition, pre-combustion chamber type, lean burn engine developed by Mitsubishi Heavy Industries, Ltd. in 1990, we developed the high power, high efficiency KU30GA gas engine that uses liquid fuel for pilot ignition by injecting a minute amount of gas oil into the pre-combustion chamber to initiate compression ignition.

2. Features of KU30GA gas engine

2.1 Engine main specifications

The engine main specifications are shown in **Table 1** and the cross section in **Fig. 1**. **Table** 2 shows a comparison with the conventional spark ignition KU30G engine. In comparison with the KU30G engine, although the KU30GA gas engine size is the same, the brake mean effective pressure P_{me} greatly increases from 14.1 bar to 19.6 bar, so that with 12–18 cylinders, one KU30GA can now provide output from 3.7 to 5.8 MW.

The power generation efficiency was enormously

Table 1 Specifications of KU30GA gas engine

			12KU30GA	14KU30GA	16KU30GA	18KU30GA
No. of cylinders			12	14	16	18
Rated	(50Hz)	(kW)	3 800	4 450	5 100	5 750
output	(60Hz)	(kW)	3 650	4 250	4 900	5 500
Model			4-stroke vee-type-gas engine with turbocharger and air cooler			
Cylinder diameter		(mm)	300			
Stroke		(mm)	380			
Engine speed		(rpm)	720/750			
Ave. piston speed		(m/s)	9.1/9.5			
Fuel gas			13A gas			
Combustion method			Pre-combustion chamber type lean burn system			
Engine weight		(t)	40	48	54	60

Table 2 Comparison with spark ignition engine

Model		KU30G	KU30GA
Ignition method		Spark ignition	Pilot ignition system
Engine output	(MW)	2.7－4.2	3.7－5.8
Brake mean effective pressure	(bar)	14.1	19.6
Efficacy at generator terminal	(%)	39.3	42.5
Engine thermal efficiency	(%)	40.5	43.8
NOx emission	(g/kWh)	1.0	0.5

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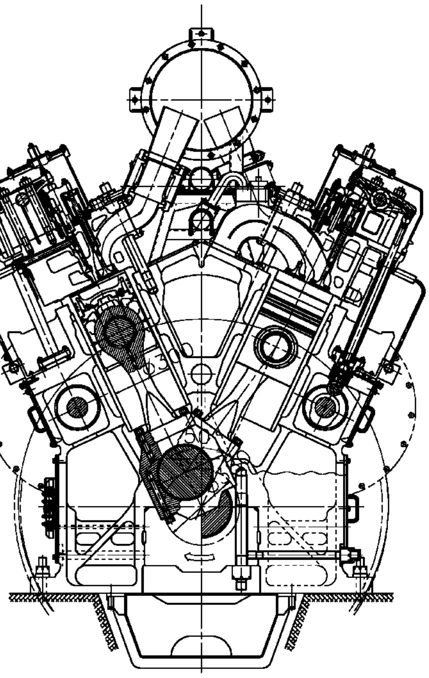

Fig. 1 Cross section of KU30GA gas engine

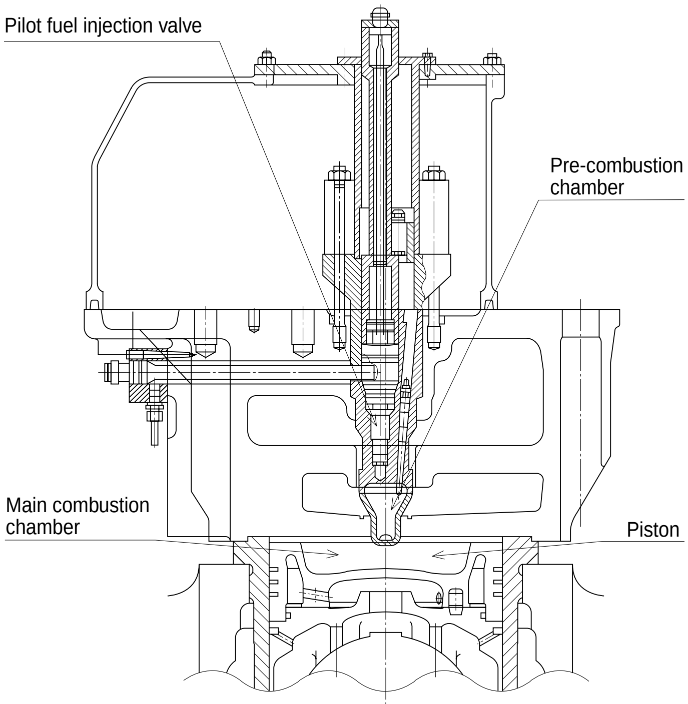

Fig. 2 Combustion chamber
The KU30GA uses a pilot ignition system where ignition is performed by injecting liquid fuel into the pre-combustion chamber.

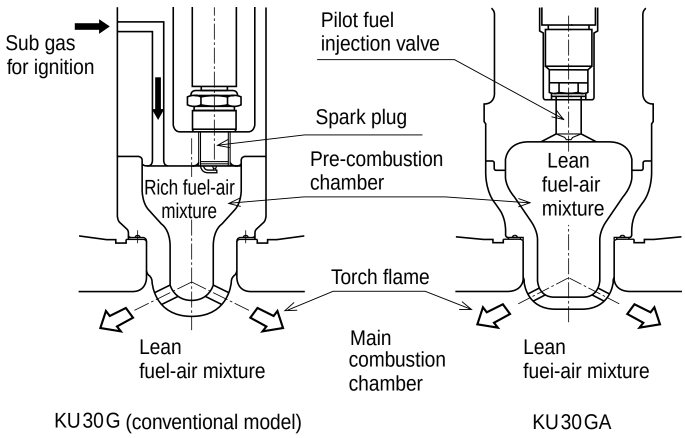

Fig. 3 Comparison of construction of combustion chamber
Construction comparison of combustion chamber of conventional model KU30G and KU30GA

increased from the conventional 39.3% to 42.5%.due to improved combustion by adoption of the pilot ignition system, improved mechanical efficiency obtained by increasing the power, improved cycle efficiency from adoption of the variable geometry (VG) turbocharger, and adoption of the knock detection and control system. By combining exhaust heat and hot water heat recovery, the plant overall efficiency reaches a peak of 71%.

By keeping the pilot fuel quantity to 1% or less of the total fuel quantity, NOx exhaust emission is kept to 0.5 g/kWh or less, a level that will comply with the stricter emission regulations in future.

2.2 Combustion method

Fig. 2 shows the cross section of the KU30GA combustion chamber, and **Fig. 3** compares it with that of the conventional KU30G. The KU30G is based on a premixing lean burn system using spark plug ignition in the pre-combustion chamber. In this system, a spark plug ignites rich fuel-air mixture in the pre-combustion chamber located in the middle of the combustion room. The torch flame from the pre-combustion chamber then ignites the lean fuel-air mixture in the main combustion room. However, because of the higher output accompanying higher compression pressure, the required discharge voltage on the spark plug has to be enhanced, and the replacement life is shortened. Therefore, under the increased power operation by means of spark plugs, the life time of them would be expected rather shorter, and alternative endurable plugs are not currently available. To solve this problem, KU30GA applies the pilot ignition system as a substitute for the spark ignition system. This new system eliminates the dissatisfactory feature of spark plug system, and supplies the most reliable ignition-characteristics, making the engine introduce higher compression pressure and higher ignition energy.

2.3 Pilot fuel injection system

Fig. 4 shows the pilot fuel injection system of the KU30GA. The pilot fuel injection system forms a part of a common rail system that enables the injection quantity, injection timing, and injection pressure to be changed freely as required. The high-pressure pump is driven by the camshaft timing gear of the engine, and the fuel accumulated in the rail is injected into the pre-combustion chamber of each cylinder through the solenoid valve-driven injection valve. This makes it possible to provide optimum pilot in-

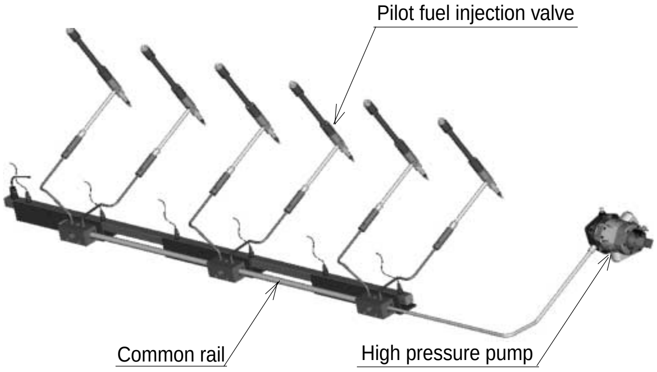

Fig. 4 Pilot fuel system
Pilot fuel injection system using common rail system is shown.

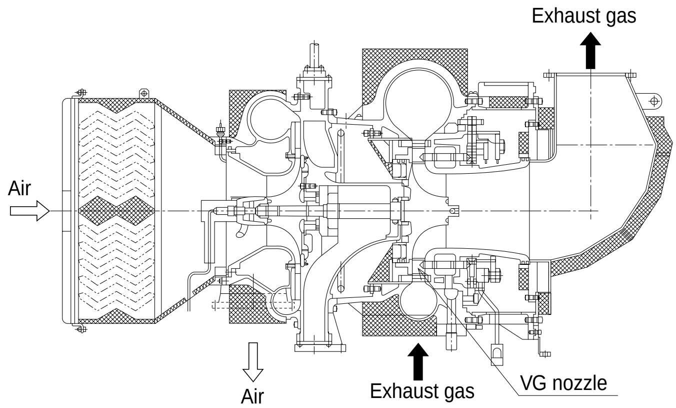

Fig. 5 Cross section of MET-SRVG turbocharger

jection under all the operating conditions. The deviations of injection quantity and injection timing among the cylinders are controllable, and fixed ignition is also possible for each cylinder.

2.4 Air-fuel ratio control system

Since the air-fuel ratio in the spark ignition KU30G engine was adjusted by release of charged intake-air, boost air was wasted in this method. This means there is also energy loss. For the KU30GA, a VG (variable geometry) turbocharger developed by MHI is used, and is capable of adjusting the boost pressure by changing the angle of the nozzle blades on the turbine side even during operation. This enables control of the air-fuel ratio without wasting boost air and improves efficiency. This improvement effect is remarkable on the low load range in which discharge quantity of boost air is relatively larger. **Fig. 5** shows the cross section of the MET-SRVG turbocharger mounted on the KU30GA.

2.5 Knocking control system

Premixing-combustion engines including the KU30GA and the KU30G are apt to sometimes produce abnormal combustion called knocking, especially when the load is placed in higher range. Knocking, as a rule, increases the risk of damage to the main components surrounding main combustion rooms. Hence, some measures such as ignition retardation are necessary to prevent knocking. On the other hand, thermal efficiency becomes higher and higher as the engine operating point approaches the knock limit closer and closer. As a result, it is important to operate the engines as close to the limit with an appropriate margins as possible. This margin is inevitable because of unexpected factors such as change in fuel quality, hot spot occurrence on combustion chamber walls and so on. The KU30GA engine constantly monitors knocking and performs prevention control when knocking occurs so that operation is possible under conditions close to the knock limit. This knock control system is standard equipment, enabling operation at optimum efficiency.

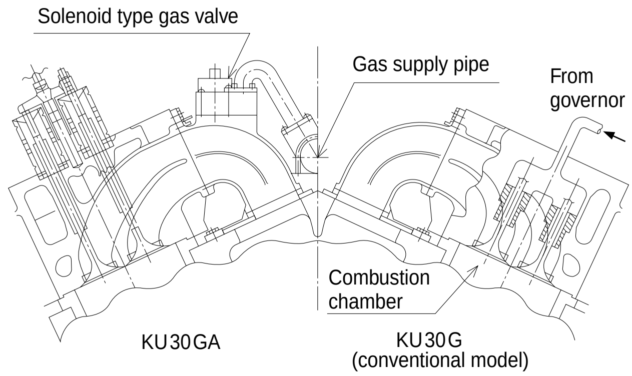

Fig. 6 Comparison of fuel gas supply
Comparison of fuel gas supply in conventional model and KU30GA. KU30GA has an electronically controlled gas supply valve.

2.6 Gas supply system

Fig. 6 shows the gas supply system of the KU30GA and the conventional KU30G. In the spark ignition type KU30G, the fuel gas quantity supplied to the main combustion room is regulated in a group by the governor valve located at the engine inlet, then the fuel gas is supplied to each cylinder via the gas valve integrated with the inlet valve.

In contrast, the KU30GA has a control system whereby the controller regulates the supply timing and the supply quantity using a solenoid type gas valve installed on the inlet port of each cylinder. This makes it possible to suppress air-fuel ratio deviation among the cylinders, which suppresses deviation between the cylinders in combustion and the knock margin, so that all cylinders can operate more uniformly near the knock limit, providing improved thermal efficiency. In connection with supply timing, supply pressure and supply method, degree of freedom has been expanded. Since the gas is mixed further upstream than for the KU30G, more uniform fuel-air mixture formation is possible. This also contributes to improvement of the knock margin. In development tests, extensive combinations of supply timing, supply pressure and supply method were compared and the optimum supply conditions were adopted from the measurement results of the fuel-air

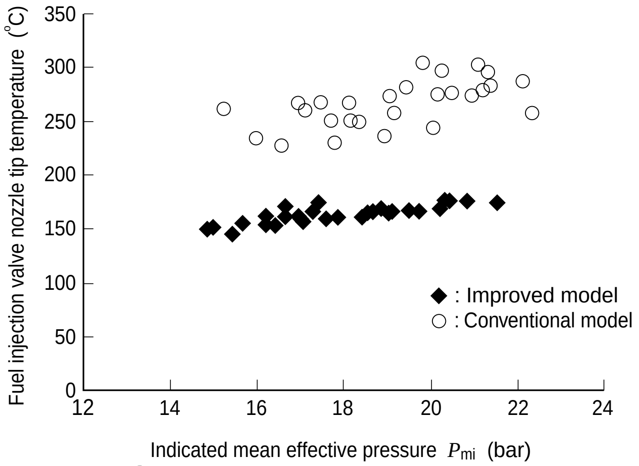

Fig. 7 Nozzle tip temperature
Nozzle tip temperature of fuel injection valve for pilot injection is shown. By improving the seat, the nozzle tip temperature has been reduced by approx. 100°C.

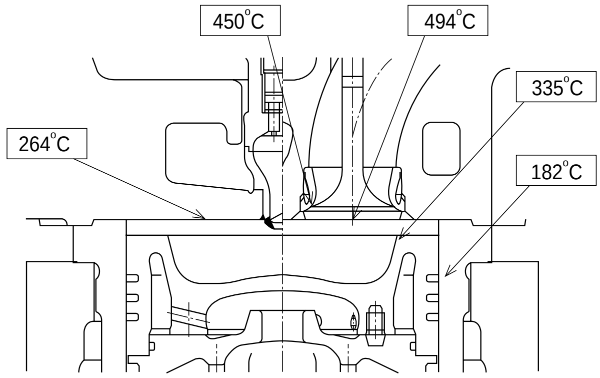

Fig. 8 Temperature of combustion chamber
Temperature of parts surrounding the combustion chamber is shown.

mixture concentration distribution and knock limit.

The method of controlling the gas quantity just before the cylinders in the KU30GA improves engine dynamic response.

2.7 Total control system

The DIASYS total control system developed by MHI regulates a total of six systems that include pilot injection, air-fuel ratio control, knock control, gas supply, boost air temperature control, and abnormal combustion monitoring. DIASYS also controls the overall electricity generating equipment, including the auxiliaries. DIASYS hereby is a highly reliable control system with a proven track record as the main controller of thermal power plants. DIASYS transmits information about the engine and auxiliaries via telephone line to the MHI Engineering and Service Divisions, acting as the nucleus of the remote monitoring system that can constantly monitor the condition of the power plant.

2.8 Reliability

Except for the main parts surrounding the combustion room, most KU30GA's main parts such as the crankshaft, engine frame, and bearings are the same as the parts of the highly reliable KU30A (P_{me}=20 bar) diesel engine, of which over 200 units have been produced. The common use of the main parts makes the KU30GA highly reliable.

Chrome ceramic rings that have been proven in diesel engines are used for the piston rings, improving ring-liner tribology and reducing wear.

3. Development testing

3.1 Test engine

The spark ignition type 12KU30G engine operating as generator equipment at the MHI Yokohama Dockyard & Machinery Works, Kanazawa Plant was converted to a 6-cylinder, pilot ignition engine for performance and reliability verification testing. First only one cylinder was converted to pilot ignition for comparative testing to establish optimum performance and verify reliability. All cylinders were then converted for final checking of performance and verification testing of the control system and all other systems.

3.2 Reliability verification test

During development of the KU30GA, how to prevent fuel coke clogging the nozzle holes of the pilot fuel injection valve was a matter of concern. In the case of micropilot ignition, the concern is that the injection quantity is extremely small compared with a standard diesel engine, because the cooling effect of the fuel itself on the injection nozzle is small, and the nozzle heats up and fuel coke clogs the nozzle holes. To solve this problem, we measured the actual temperature surrounding the pre-combustion chamber and used FEM analysis to determine the heat flow in order to develop an effective injection valve cooling method. By optimizing the design of the pre-combustion chamber and the position of the injection valve seat, as shown in **Fig. 7**, the originally measured temperature was reduced by approximately 100°C, to the target temperature of 180°C.

Fig. 8 shows temperature measurement results for the typical points around the main chamber room. The temperature are kept to the same levels as those of the KU30G. This also proves the good reliability of the KU30GA.

3.3 Performance Test

In order to deliver high efficiency in performance tests on the actual engine, parameters such as the compression ratio, piston design, pilot injection conditions, pre-combustion chamber specifications (capacity, number of nozzle holes, nozzle diameter, nozzle angle), and valve overlap timing of suction and exhaust strokes were tested for optimal conditions. At the brake mean effective pressure P_{me}=20 bar, equivalent to the target output, a thermal efficiency of 43.8% was achieved. By keeping the pilot injection quantity to 1% or less of the total fuel quantity, we succeeded in reducing NOx to 0.5 g/kWh or less. This NOx level fully meets future NOx restrictions and is a departure point for achieving further reduction.

4. Conclusion

MHI has developed the KU30GA gas engine using pilot ignition system as the next generation of high efficiency, low pollution gas engine to replace the conventional spark ignition gas engine KU30G. This high performance gas engine uses the latest technology such as a common rail injection system and VG turbocharger for the purpose of achieving thermal efficiency of 43.8% as a result of various optimization tests. Using a pilot injection quantity of 1% or less of the total fuel quantity provides stable combustion with an extremely low NOx level of 0.5 g/kWh. The main parts are the same as those of the KU30G diesel engine, of which over 200 units have been produced, and the test results have enabled us to reduce the combustion chamber temperature to the actual level of diesel engines. Our next target is to improve lean burn combustion technology and efficiency while contributing to environmental preservation.

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