Development of High Density Gas Engine 28AG

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The 28AG engine was developed since the market requires higher efficiency gas engines. As a result, 47.6% power generation efficiency, which is the highest in the world, was confirmed. Since the micro pilot ignition system, which this engine has adopted, can obtain powerful ignition energy, quick positive combustion of fuel-air mixture is enabled. Thereby, about the same high power generation efficiency and high output as a diesel engine can be obtained. The key points of highest power generation efficiency achievement are the original ignition system, adoption of the Miller cycle, optimization of pre-combustion chamber specification, optimization of fuel-air mixture formation process, and others.

1. Introduction

The low-pollution gas engine using gaseous fuel is superior to the diesel engine using liquid fuel such as marine diesel oil because there is no discharge of smoke or PM (particulate matter) and NO_x concentration is low in the exhaust gas.

Recently, the gas engine, which has been recognized for its low-pollution performance, has been increasingly selected in place of the diesel engine as the prime mover for driving a generator, and demand for gas engines is increasing. To enhance the conformance of the gas engine with the market environment, its technological development was accelerated, and as a result, its output power and electric thermal efficiency have been raised and are now comparable to those of the diesel engine.

Against such a background, large gas engines have mostly been used for co-generation systems for chemical and machinery industries and by such users as ESCOs (Energy Service Companies) and IPPs (Independent Power Producers), and higher efficiency has been demanded. With the 28AG gas engine, we have worked to meet the needs for higher efficiency and have achieved an electric thermal efficiency of 47.6%, the world's highest.

This engine has been developed jointly by Ishikawajima-Harima Heavy Industries Co., Ltd. (hereinafter called IHI) and Niigata Power Systems Co., Ltd. (hereinafter called NPS) through the fusion of many developments in gas engines technology, the market performance of NPS and the analytical and IHI's Corporate Research & Development element technology. It is outline follows.

2. Introduction of 28AG Gas Engine

Main specifications are shown below and the development process in **Fig. 1**.

Engine type	18V28AG
Power generating output	
50 Hz	5 800 kW
60 Hz	5 500 kW
Engine Speed	
50 Hz	750 min^{-1}
60 Hz	720 min^{-1}
Brake mean effective pressure	1.96 MPa
Weight	57 000 kg
Electric thermal efficiency	47.6%

(Note) :
- NOx emission is less than 600 ppm (O_2 : 0% conversion)
- Depending on fuel properties
- 5% tolerance included

In the co-generation market for a power range of 1 to 3 MW, the 22AG series gas engines have already made significant achievements. The 28AG gas engine has been developed for the higher output market based on the combustion technology of the micro-pilot ignition system adopted for this 22AG series and gas engine control technology. The 28AG gas engine was designed for gas fuel based on the 28HLX high performance

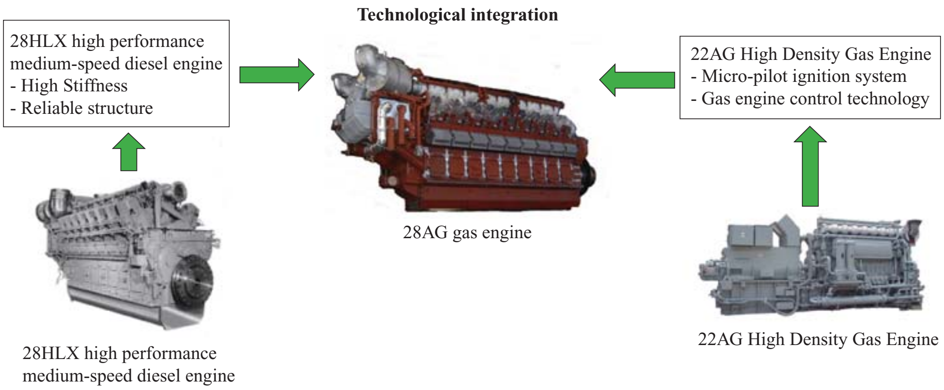


Fig. 1 Development process of 28AG engine

medium-speed diesel engine that was well proven in the market. Since the main structures such as the crankshaft and crankcase are the same as those of the diesel engine, the engine inherits the reliability of the diesel engine.

2.1 Micro-Pilot Ignition System

This engine uses the micro-pilot ignition system (**Fig. 2**). The micro-pilot ignition system uses diesel oil equivalent to about 1% of the supplied energy as its ignition source and can provide more powerful ignition energy than the conventional spark ignition system. The powerful ignition energy realizes quick and reliable combustion of a lean mixture. It can therefore realize the same high electric thermal efficiency and output power as the diesel engine.

Though different in ignition system, it maintains the same low NO_x emissions in exhaust gas as the conventional gas engine, because it adopts the same lean-burn system as the conventional system. The NO_x emissions mainly depend on the quantity of pilot oil, but since the quantity of the pilot oil used is very small, it can maintain a low NO_x level and can meet the emission standards stipulated in Japan's Air Pollution Control Law.

The powerful ignition energy makes it possible to use as fuel gas such gases with low calorific value (about 1/5 against the calorific value of city gas 13A) as the pyrolysis gas and sewage sludge gasification gas.

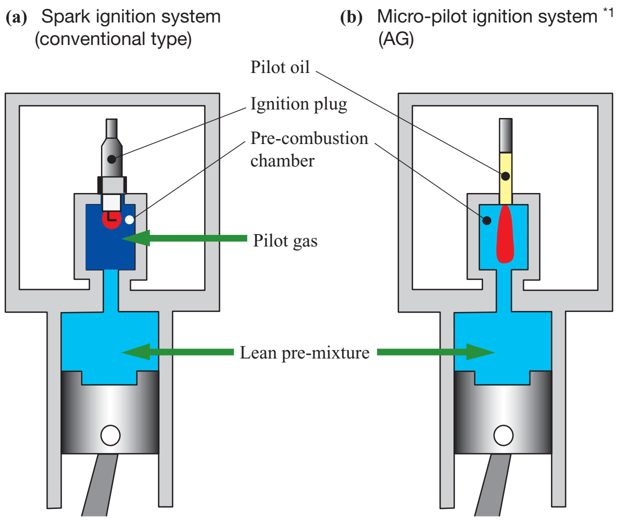
2.2 Starting System

To improve the ignition in low-speed condition at starting, the starting system using the ignition plug is adopted. This spark plug starting system is NPS's own technology [1] and the adoption of the micro-pilot ignition system ensures failure-free starting. **Figure 3** shows this starting system with the spark plug.

2.3 Control System

Figure 4 shows the control block diagram of the engine. Since the fuel injection pump developed for supplying a small quantity of liquid fuel (pilot oil) is made to be similar in structure to the simply structured pump of the diesel engine, it is superior in maintainability.

The fuel gas is supplied to the engine by an EFI (Electronic Fuel Injection) system consisting of engine controller, governor driver, and solenoid valves provided for the cylinders. The engine controller optimally controls the supply timing and supply amount of the fuel gas to maintain the best performance, and the exhaust



(Note) *1: Ignition power is more than 5 000 times of conventional type one

Fig. 2 Powerful ignition energy of micro-pilot compression ignition system

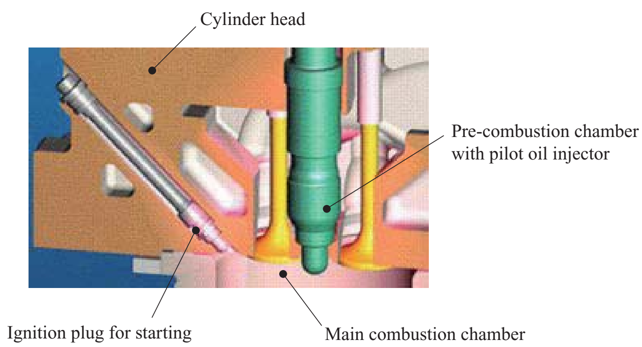


Fig. 3 Spark start system

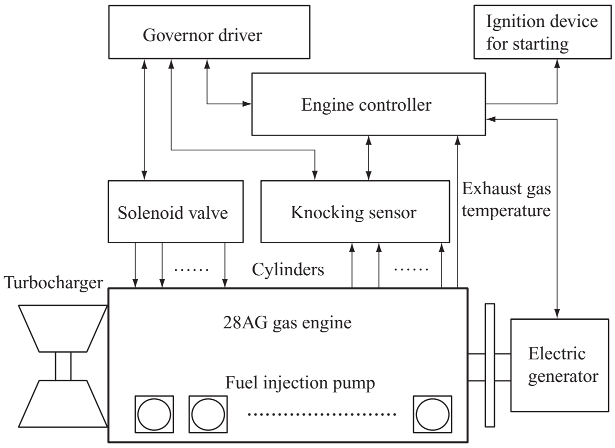


Fig. 4 Engine control block diagram

temperature of each cylinder is automatically controlled by this EFI system.

It is also equipped with a knocking control system. If knocking occurs with any cylinder, it detects it and automatically reduces the supply of fuel gas to the cylinder to avoid the knocking, ensuring a stable continuous operation.

3. High Efficiency Gas Engine Technologies

The key factors for achieving the world's highest electric thermal efficiency are matching the high efficiency turbochargers and the Miller cycle and optimizing pre-combustion chamber specifications and mixture the formation process.

That is, the highest electric thermal efficiency has been achieved by minimizing knocking through the optimization of flame propagation from the pre-combustion chamber and making uniform the mixture, in addition to the effect of adopting the Miller cycle.

3.1 Miller Cycle

With reciprocating engines such as gas engines, the electric thermal efficiency increases as the compression ratio increases, but increasing the compression ratio is limited because knocking will occur. With the Miller cycle, on the other hand, more energy can be taken out, making it possible to enhance the efficiency by making the expansion ratio larger than the compression ratio by setting the closing timing of the intake valves faster than the normal setting. Since the effective compression ratio decreases, the margin against the knocking is increased. **Figure 5** shows the principle of the Miller cycle. By utilizing this margin, further adjustment for improving the efficiency can be performed and the efficiency can be further enhanced.

If the closing timing of the intake valves is set faster than the normal setting, however, the mixture in the combustion chamber expands as shown in **Fig. 5**, making it necessary to supply the mixture of high density, especially air for combustion in a short time. The turbochargers are therefore required to realize higher pressure ratio. With the 28AG gas engine, this problem is solved by using the turbochargers of high pressure ratio and high efficiency of Turbo Systems United Co., Ltd./ABB Turbo Systems Ltd. (Switzerland).

To improve performance, the opening/closing timing of the intake valves and the compression ratio must be optimized. In the development of this engine, therefore, the engine performance was predicted by cycle simulation and then test parts incorporated in the actual engine based on the calculation results were manufactured. Then the actual engine performance was checked. Since the parts to be changed when the Miller cycle is adopted are main engine parts such as camshafts and pistons, simulation greatly reduced the development expenses and shortened the development period.

3.2 Optimization of Pre-Combustion Chamber Specifications and Shape of Main Combustion Chamber

The point of developing the 28AG gas engine was to fit the combustion technology of the micro-pilot ignition system of the 22AG series to the engine with a larger

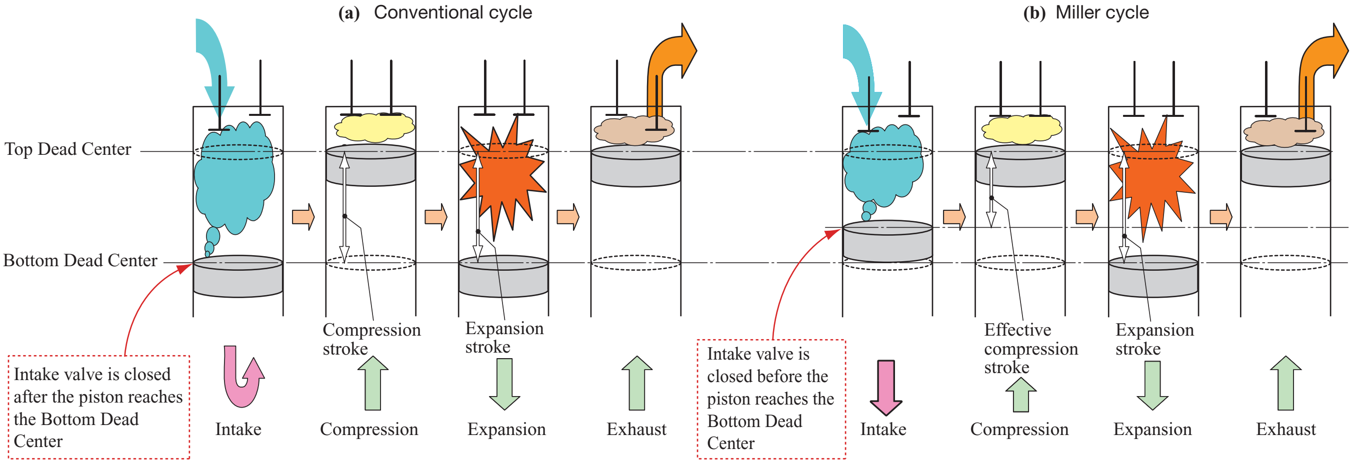
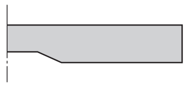
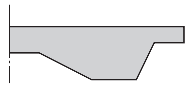
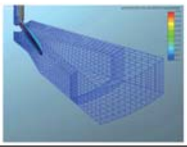
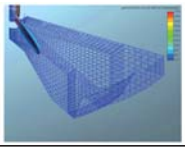
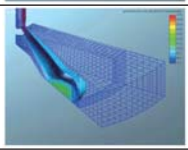
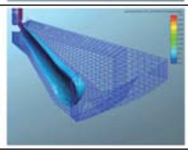
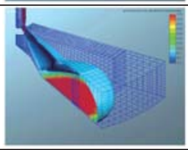
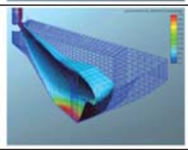
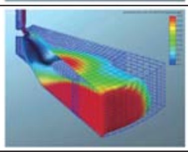
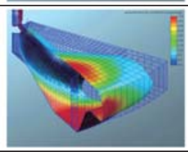


Fig. 5 Miller cycle principle

bore. Optimizing the shape of the pre-combustion chamber greatly contributed to this end. By improving the pilot jet flame from the pre-combustion chamber, the ignition source, the quenching area was reduced and the combustion period was shortened, thus improving the combustion efficiency. By forming the pilot jet flame to fit the shape of the main combustion chamber, the optimum combustion was realized and high efficiency was obtained.

Figure 6 shows an example of calculation results by the computational simulation. This calculation results show temperature distribution in the combustion chamber for each crank angle to research the propagation of the pilot jet flame for different combustion chamber shapes. If the flame touches the combustion chamber wall surface relatively early, combustion is slowed and the subsequent flame propagation speed is reduced. That is, the main combustion chamber geometry must be provided with sufficient space for the propagation of the flame just after it is injected from the pre-combustion chamber, and the pilot jet throats of the pre-combustion chamber must be orientated to suit the main combustion chamber geometry.

Item	Combustion chamber type A	Combustion chamber type B
Sectional shape of combustion chamber		
1 deg. CA after Top Dead Center		
3 deg. CA after Top Dead Center		
6 deg. CA after Top Dead Center		
15 deg. CA after Top Dead Center		

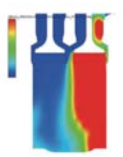
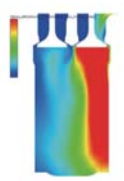
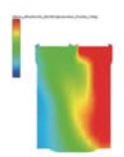
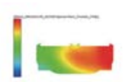
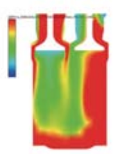
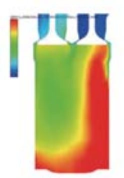
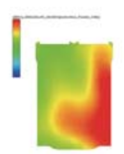
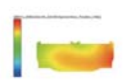
(Note) Temperature distribution : the light blue surface is isothermal surface at 1 000 K
CA : Crank angle

Fig. 6 Calculation results of jet flame from pre-combustion chamber

3.3 Optimization of Mixture Formation Process

If non-homogeneous concentration occurs in the lean mixture in the main combustion chamber, the fuel rich region becomes a factor in the production of NO_x and knocking and reduces the adjustment margin for efficiency improvement. In the lean region, quenching occurs to become a factor in increasing unburned gas in the exhaust gas. That is, promoting a lean mixture is indispensable for improving efficiency.

For grasping the fuel mixing conditions, 3D-CFD (three-dimensional Computational Fluid Dynamics) was used. The calculation model included opening/closing of the intake valves and piston motion in the intake stroke. The behavior of the gas fuel injected into the intake port and flowing into the combustion chamber while mixing with the charge air, being compressed and reaching the point just before combustion was clarified by calculation (**Fig. 7**). The calculation result revealed that the uniformity of a lean-mixture concentration in the main combustion chamber changes depending on the shape and position of the fuel gas injection nozzle. As the fuel gas injection nozzle is away from the main combustion chamber, the mixing is promoted, but as an adverse effect, the fuel gas remaining in the intake port increases. From the above, it was confirmed that the

Stroke	Intake stroke			Compression stroke	
Crank angle	60 deg. CA	120 deg. CA	180 deg. CA*1	240 deg. CA	320 deg. CA*2
Fuel gas injection nozzle type A					
Fuel gas injection nozzle type B					

(Note) *1 : Bottom Dead Center
*2 : Before ignition

Fig. 7 Calculation results of fuel-air mixture concentration gas fuel supply pressure and injection timing are also factors that promote mixing. Based on these calculation results, these factors were optimized and efficiency was improved.

4. Conclusion

The 28AG gas engine was developed to cope with the needs for higher efficiency in the large gas-engine markets, and achieved electric thermal efficiency of 47.6%, the world's highest.

This development has been promoted jointly by Ishikawajima-Harima Heavy Industries Co., Ltd. and Niigata Power Systems Co., Ltd. IHI was in charge of analysis through numerical simulation and fundamental experiment, and NPS was in charge of matching tests with the test engine. Both companies carried out the developing work efficiently. In addition to the micro-pilot injection system to realize high efficiency and high output, the Miller cycle was adopted and the pre-combustion chamber particulars and mixture formation process were optimized to improve the efficiency, realizing the world's highest level of electric thermal efficiency.

REFERENCES

(1) Niigata Power Systems Co., Ltd. : Japan Patent No. 3820032