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Experiences on 1 to 6 MW class highly adaptable micro-pilot gas engines in one hundred fields and over fifty thousand running hours

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Abstract: NIIGATA has a success story about original micro-pilot gas engines that are high-density gas engines with BMEP of 1.96MPa. NIIGATA 22AG series have been applied as the key hardware in cogeneration systems in Japan since 2002. The total delivered number is over 100 units, and generating power is over 200MW. The 22AG series consist on in-line type 6, 8, V-type 12, 16, 18 cylinders, which cover from 1MW to 3MW. Most of all engines have been in operation approximately 8,000 hours at BMEP 1.96 MPa continuously in a year.

The first delivered three 8L22AG engines have since been operated continuously every day, which the running hour per year corresponds to 8000 hours. There were no serious problems until now, July 2009. The total operation time is 55,000 hours and minimum engine stop maintenance interval is 4,000 hours as scheduled.

The engineering findings that the performance of various field applications and their operation history, durability of engine parts are described in this paper. Field results for one-year experience of our 6 MW class 28AG type gas engines, which were delivered in 2008, are also described.

In Japan, specific operation and special adjustment for individual cogeneration system is required according to the unique power supply circumstances. NIIGATA cogeneration system based on AG series gas engine has been progressing to have robustness in order to meet these individual requirements. Some specific examples are introduced here.

In some region, commercial electric power failure occurs by thunder sometimes and it is a big risk for customers production. When service electricity happens to stop suddenly, normally engine-generating system is stopped according to the reason of grid system. AG cogeneration system can survive for such case with still keeping power generating. This robust operation can provide the safety plant running, for example for chemical plant being desired to keep the reaction temperature constant. Figure 1 shows the time chart of the sudden load decrease from full load to 55% load.

Some factories in Japan are located in the area like mountainous region where fuel gas pipeline networks do not spread enough and in such case LNG satellite supply fuel is used. Property of fuel gas evaporated from LNG is not always constant so the heating value varies with time. The property variation causes knocking phenomena. Highly reliable knocking control system with fast response is essential.

Many gas engine generation systems do not only use the power generated by own gas engine systems but some quantity of commercial electricity. One of the customers needs is to keep the amount of commercial electricity consumption constant to low level. In some plant, the frequency of engine start/stop has to increase to cope with the power demand. The frequent start/stop is not good for the engine parts. NIIGATA patent; spark start micro-pilot system is clear function to secure frequent start/stop operation and quick power generation.

INTRODUCTION

The lean-burn technologies have been applied to medium sized gas engines since approximately 20 years. Thanks to lean-burn technology, adiabatic flame temperature is lower and NOx emission is sufficiently low without catalyst, which derives higher BMEP and thermal efficiency. The characteristics of engines compared medium speed diesel and old gas engines in about 20 years ago to modern lean-burn gas engines are shown in Figure1. Power output and efficiency of the modern gas engine used as key hardware of cogeneration systems are comparable or higher than diesel engines while the advantage of low emission (NOx, particulate matter) performance of gas engines are maintained. Figure 2 shows the potential of gas engine grown continuously with increasing expectations for both land-based cogeneration and low NOx marine engine.

The authors have proposed micro-pilot systems as a technology in order to improve power output and efficiency of gas engines[1]. 1~3MW class Micro Pilot gas engines have been in service from 2002[2], and case studies of using pyrolysis gas as fuel to take advantage of the technological superiority offered by micro-pilot systems[3] were reported.

The operational histories of more than 100 micro-pilot gas engines operating in Japan and consistent service operation more than 57,000 hours with first delivered engines are reported in this paper. The paper also provides long-term field operational data (e.g. operating history, performance changes, component durability) acquired to date, together with data on performance in the field over one year for the first 28AG 6 MW class gas engine recently developed.

LNG-satellite-supplied fuel is often used in engines installed for power generation at plants in regions of Japan lacking extensive gas pipeline networks. The characteristics of this infrastructure raised practical technical issues, such as combustion control for varying gas characteristics. There are unique operating requirements that the engines are to be controlled to minimize power consumption from commercial power supplies, to respond to increasing start-stop frequencies with power demand fluctuations, and to maintain their operations after a commercial power supply fails. The paper also describes the suitable techniques for handling these requirements in Japanese market.

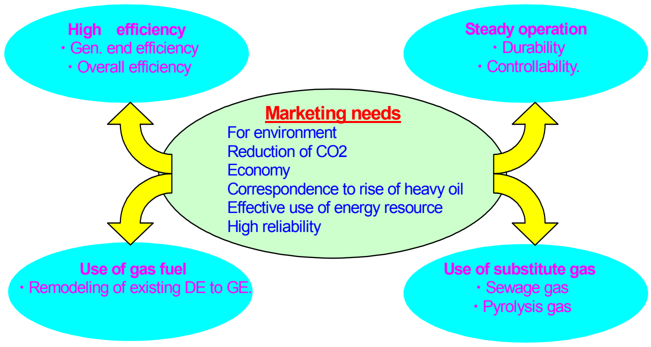

Figure 2 - Potential of gas engines

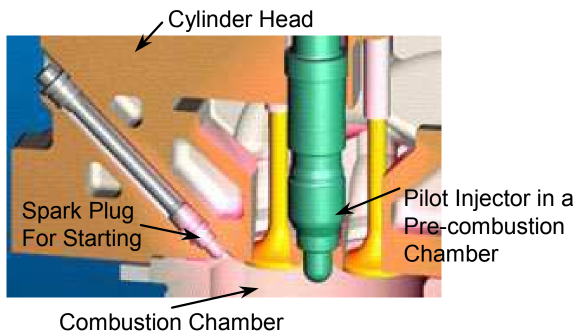

Figure 3 - Spark start system

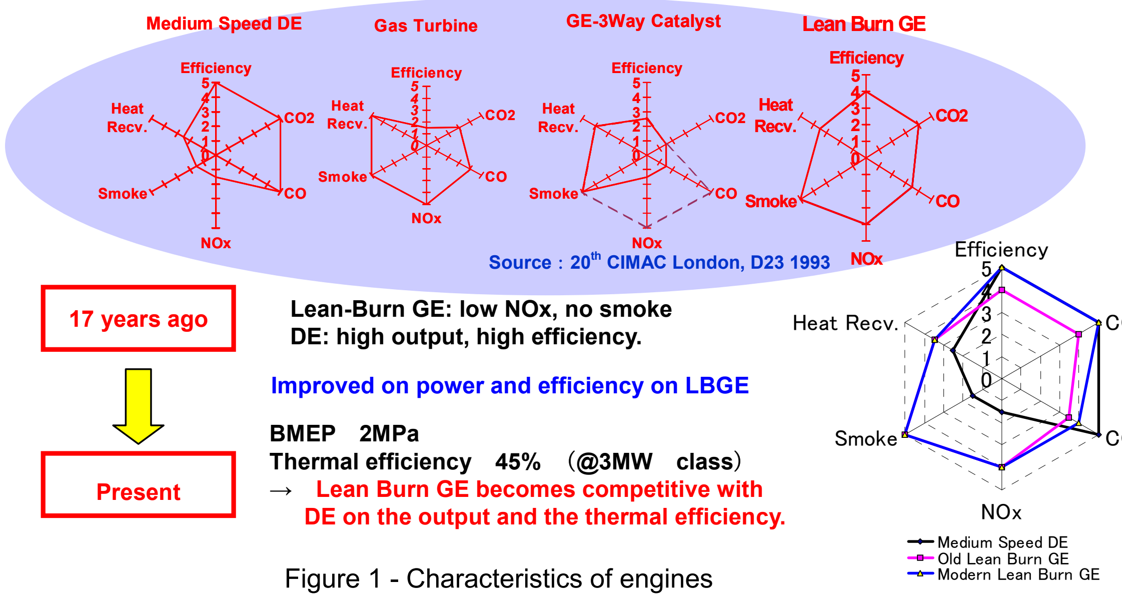

Figure 1 - Characteristics of engines

AG Engine Description

AG Engine Overview

As shown in Table 1, the AG engine series consist of six models for two engine configurations covering outputs from 1 to 6 MW. Besides, the spark start system as shown in Figure 3 used in 22AG gas engine is also employed in the recently developed 6MW class 28AG gas engine. This starting system technology developed originally by Niigata Power Systems ensures reliable starting operation.

Figure 4 illustrates the engine control block diagram for of AG series. The fuel injection pump used to supply a small volume of liquid fuel (pilot oil) is the same pump used in 22AG gas engines. Consisting of an engine controller, governor driver, and solenoid valves attached to each cylinder, the EFI (electronic fuel injection) system is also the same as used in the 22AG gas engines. The whole control system comprises a fuel gas supply system, output control system, and knocking control system developed over the years.

Figure 5 shows the typical start-up and load control data for a 28AG gas engine. The starting system and engine control system described above ensures reliable start-up and rapid power output control even for large 6 MW class gas engines, just as with gas engines in the 1 MW to 3 MW range, supporting their status as superior power-generating engines.

Operation Achievements of AG Series Gas Engine

The authors assessed the performance of 8L22AG engines annually over the seven and a half years since their first delivery in 2002. These engines had achieved 4,000 hours non-stop operations at high output of 1.96 MPa without major troubles. Thus, the minimum maintenance interval became 4,000 hours after that. Currently, more than 100 engines have been operated in a number of plants, with a total power generation capacity of 210 MW. There are several plants that use low-calorie gas such as sewage gas or synthesis gas. The high-energy micro-pilot system provides them reliable ignition ability.

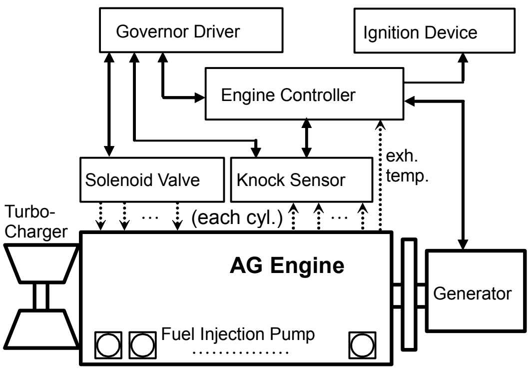

Figure 4 – Engine control block diagram of AG series

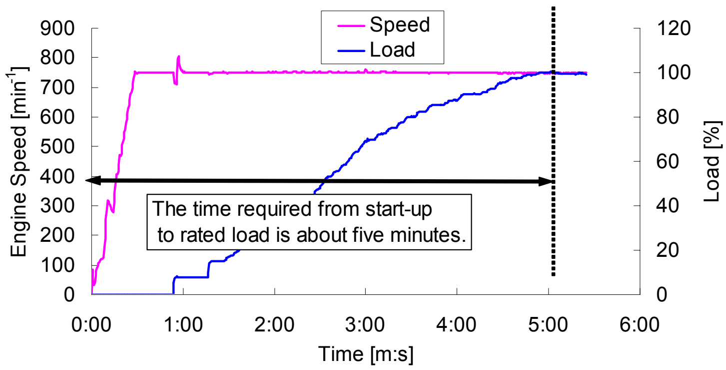

Figure 5 – Start-up and load control

Table 1 – Line-up of Advanced Gas Engine series

MODEL	6L22AG	8L22AG	12V22AG	16V22AG	18V22AG	18V28AG
Type	Turbo charged, 4cycle gas engine with air cooler					
Configuration	In-line		Vee-form			
Cylinders	6	8	12	16	18	
Bore	220 mm					295 mm
Stroke	300 mm					400 mm
Displacement	11.4 L/cyl					27.3 L/cyl
BMEP	1.96 MPa					
Generator Output 50 Hz (1000 min-1)	1050 kWe	1400 kWe	2120 kWe	2850 kWe	3200 kWe	5800 kWe
Generator Output 60 Hz (900 min-1)	950 kWe	1260 kWe	1910 kWe	2560 kWe	2880 kWe	5500 kWe
Ignition system	Micro pilot fuel oil (Supported by spark plug at starting)					

RESULTS OF LONG-TERM OPERATION IN FIELD

Thermal Efficiency Trends

The first three 22AG gas engines, 8L22AG, have been in operation as key hardware of cogeneration system in Japan since July 2002. Output of each engine is 1,260 kW/900 min^{-1}, and all three engines have been running continuously. Cumulative operating time of each engine reaches 57,000 hours. Recent status shows thermal efficiency of 40% and NOx emissions of 500 mg/m^3N at O_2 5% are maintained with no major troubles.

Figure 6 illustrates the variations of thermal efficiency and generator output of 57,000 hours of operation. Despite operating for over seven and a half years, efficiency has not decreased noticeably, and in some cases has even increased. This performance is attributable to highly improved engine adjustment technologies, e.g. optimization of pilot oil injection timing, air-fuel ratio control, and knocking control. Stable and high performance operations have been obtained through four seasons in a year, with varying outside temperatures in the range of 0°C to 33°C and absolute humidity in the range of 3 g/kg to 17 g/kg. The fuel gas used has a methane number of 65.

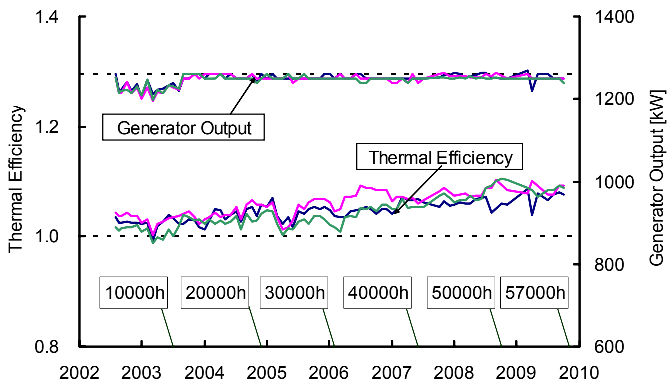

Figure 6 – Performance during 57,000 hours

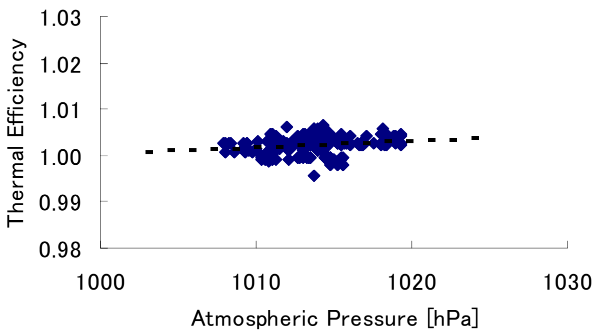

Figure 7 – Effect of atmospheric pressure

Effects of Ambient Conditions

Ambient conditions such as atmospheric pressure, temperature, and humidity affect the performance, especially the thermal efficiency of gas engines. These effects are difficult to be estimated due to the complexities of variations between different plants and the requirements to accumulate long-term operational data.

The results of studies on performance fluctuations in multiple power generation plants carried out over a period of approximately one year are described below.

(1) Atmospheric pressure

Lower atmospheric pressure generally leads lower thermal efficiency, due to the increase in workload for the turbocharger. The turbocharger supplies air to the combustion chamber at the specified air pressure (boost pressure) to ensure the amount of air needed for appropriate combustion. If atmospheric pressure becomes lower, the turbocharger needs much energy to boost the air up to the set suitable pressure. The turbocharger is driven by the thermal energy of exhaust gas. Thermal efficiency decreases by the amount of energy that is excessively consumed by the turbocharger. Figure 7 shows the relationship between atmospheric pressure and thermal efficiency for the 22AG engine at an actual plant. This relation shows that the reduction of atmospheric pressure of 10hPa results in about 0.20% of decrease in thermal efficiency as a result consistent with general theory.

(2) Inlet temperature

An increase in turbocharger inlet temperature (ambient temperature) decreases thermal efficiency. As in explained above, this is due to the increased workload on the part of the turbocharger. Air density reduces with increased temperature, meaning the turbocharger must compress more air corresponding to the reduced density to achieve the set boost pressure, which in turn consumes more energy in turbocharger and decreases thermal efficiency. Figure 8 shows the relationship between inlet temperature and thermal efficiency.

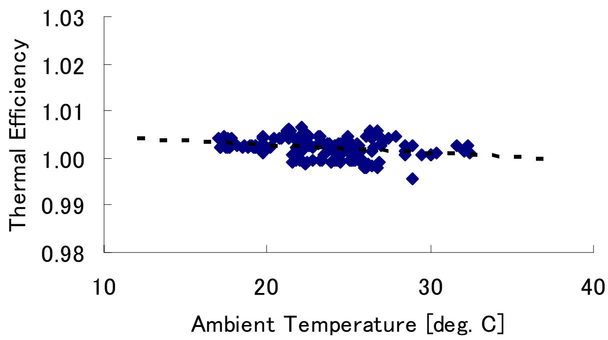

Figure 8 – Effect of ambient temperature

(3) Absolute humidity

An increase in absolute humidity decreases thermal efficiency. Increased water content in the air used for combustion causes increased vaporization of water during combustion. Then, vaporization heat is absorbed, the combustion slows and heat generation is reduced. Higher absolute humidity therefore affects combustion and reduces efficiency. However, a lower combustion temperature reduces NOx and suppresses knocking. Figure 9 shows a typical relationship between absolute humidity and thermal efficiency obtained at a number of actual plants. An increase in absolute humidity of 5 g/kg reduces thermal efficiency by approximately 0.25%. This trend follows the mechanism described above.

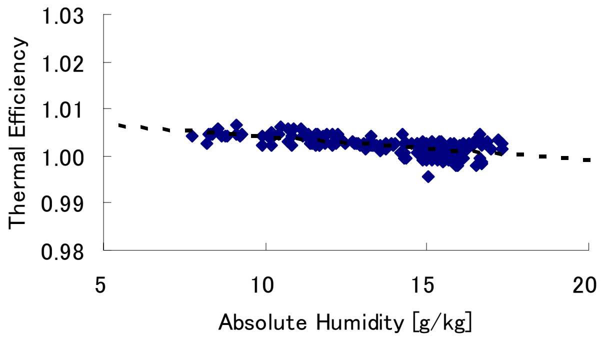

Figure 9 – Effect of absolute humidity

Lubrication Oil

Generally, the lubrication oil used in reciprocating engines must offer certain quality of anti-oxidizing properties, cleaning properties, acid-neutralizing properties, and thermal stability. For this purpose, various additives are contained in the lubrication oil. Many of the additives are derived from metal origins, which are analyzed as ash contents in lubrication oil. For diesel engines, excessive ash contents in the oil and sulphur contents in the fuel oil will form solid deposits in the combustion chamber.

As fuel oil is not applied in spark-ignition lean-burn gas engines, therefore it is not required cleaning quality or acid-neutralizing quality in the lubrication oil. In addition, combustion deposits in the combustion chamber may cause self-ignition. For this reason, ash contents in the lubrication oil for these engines are kept to minimum level.

The 22AG gas engine incorporates a micro-pilot compression ignition system, using a very small quantity of fuel oil as its ignition source. The authors had estimated how the property the lubrication oil changes through long-term field operation. Figure 10 shows one-year performance trend of the lubrication oil (8,000 operating hours) of the first delivered 22AG gas engine. Regular topping up of the lubrication oil prevented any noticeable deterioration in oil conditions, and all parameters remained within permissible limits. Therefore, it was concluded that the lubrication oil for lean-burn spark-ignition gas engine can also be used for the AG gas engines. At this present, all of the 22AG gas engines used in commercial plants use the lubrication oil with low sulfated carbon content.

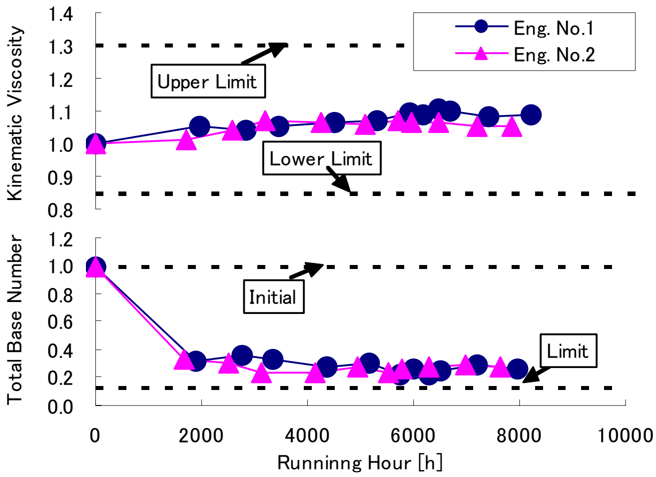

Figure 10 – Analysis of lubrication oil

Durability of components

The micro-pilot system was made possible by using fuel injection valves which effectiveness has already been demonstrated in diesel engines. The fuel injection valves can be used longer periods and offer greater durability than the spark plugs used in spark ignition systems. As described by the authors, the initial 8,000 hours of actual service for the first delivered 22AG gas engines demonstrated that the pilot oil fuel injection valve developed for the 22AG can be used for 4,000 hours of sustained operations without maintenance or failures[2].

While these engines operate at a BMEP of 1.96 MPa, it was verified that the components used in the engines meet the initially prescribed service life requirements with increasing the durability of the engines.

The authors also reported the results of overhaul inspections of key components after the first 8,000 hours of operation for the first delivered engine, together with operation data for a period 32,000 hours[2],[3]. In this paper, the overhaul inspection status after 48,000 operating hours is described additionally. The photographs in APPENDIX show the state of key components (cylinder head, inlet/exhaust valves, piston, liner, crank pin bearings) at the time of inspection. All components were confirmed to be in good condition due to regular cleaning and maintenance every 8,000 hours, demonstrating the suitability of low sulfated carbon content gas engine lubrication oil.

APPLICATIONS SPECIFIC TO THE JAPANESE MARKET

Cogeneration systems in Japan are associated with a number of characteristic operating configurations.

For example, private LNG satellite facilities may be equipped at plants in regions where gas pipeline network is not extended. In such cases, the calorific value of the fuel gas will vary over time. For other example, the engine load will fluctuate and the start-stop frequency will increase if the power supply is subjected to minimize power consumption from commercial power supplies. The power may also be supplied to prevent the stoppage of important loads in the event of commercial power supply failures. In this case, it is necessary for power systems to be able to respond to unexpected load change.

The 22AG gas engine is capable of handling such specific conditions to use in Japan. Parts of this report discuss this aspect of performance.

Important Load Survival

(1) Background

Most 22AG gas engines are used as the cores of large-scale factory cogeneration systems. Power generated by cogeneration systems is interlinked with the commercial power supply, with the commercial power supply used to supplement the output generated by the engine.

Many plants constructed around mountainous district are often attacked by thunderstorms, and power failures may occur frequently in certain regions and during certain seasons. Depending on the factory-operating configuration, power failures may stop the production line and cause significant losses to customers. Uninterruptible power supply systems can be used to handle power failures of a few seconds, but are ill-suited to handling power failures that persist for several minutes.

To cope with such stoppages, one method instantly isolates the cogeneration power generation circuit from the commercial power supply circuit and allocates the cogeneration power to the most important loads. This is known as “important load survival operation”.

Figure 11 illustrates the important load survival operation of the switching system that the high speed circuit breaker shown in this diagram can be switched circuits very quickly. In the event of a power failure, the power from the cogeneration system flows into the commercial power supply circuit, imposing an excessive load on the gas engine. The circuit breakers are used to prevent this by instantly sensing the voltage sag or power failure. Then the cogeneration system undertakes the power supply to the essential load.

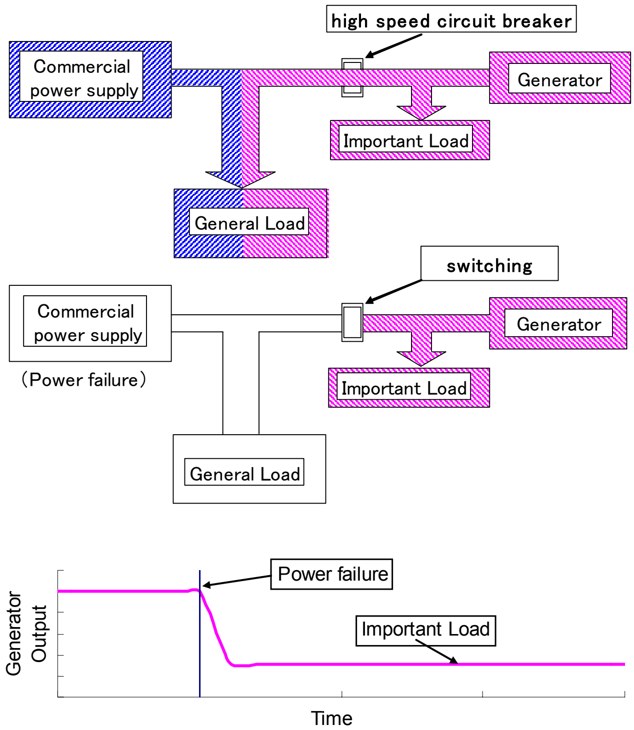

Figure 11 – Important load survival operation

Gas engines are also generally more susceptible to load fluctuations than diesel engines. With gas engines, the control of the air-fuel ratio is very sensitive. The air-fuel ratio cannot be often appropriately controlled when the load changes suddenly or fluctuates largely, causing engines to stall. For this reason, the configuration of the engine system is a key point to keep the engines running surely. The control system then had been sophisticated by the authors to keep the air-fuel ratio appropriately in the event of sudden load change. The 22AG gas engine incorporates a micro-pilot ignition system. Combined with high ignition power, this system allows the engine to meet these demands. This feature, helping the customers avoid losses associated with power failures, is highly valued by them.

(2) Technical Issues

One technical issue is engine stall caused by stoppage of the fuel gas supply solenoid valves.

With the 22AG gas engine, fuel gas is supplied to the intake port via the solenoid valve. Gas pressure acts on the solenoid valve inlet side, and the boost air pressure acts on the solenoid valve outlet side. The gas pressure is higher than the boost air pressure (hereinafter, the pressure difference between gas and air is written as "ΔP"). The solenoid valve opens when the coil force overcomes ΔP. If ΔP becomes too high, it will exceed the permissible pressure difference for the solenoid valve to be operated, and prevent the valve from opening.

The authors invented the ΔP control system which is called survival system, this system can eliminate sudden increases in gas pressure to maintain ΔP within the range of permissible pressure differences. Figure 12 shows the waveform after the modifications. The boost air pressure drops rapidly and the gas pressure follows that, and ΔP does not exceed the permissible pressure difference. This allows the operations to continue.

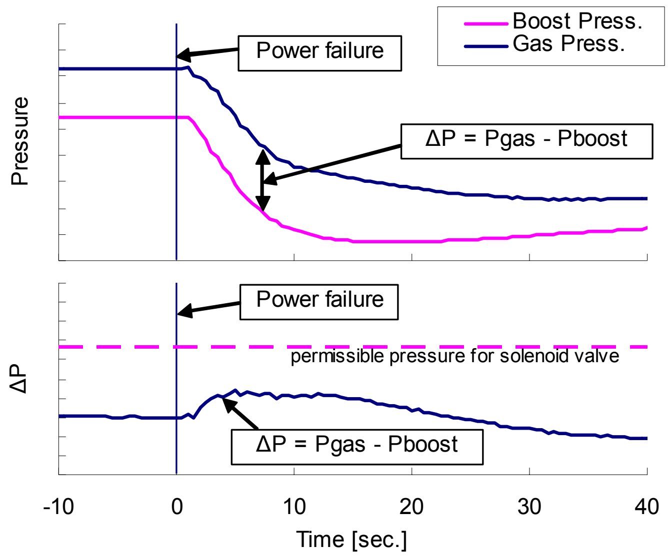

Figure 12 – Modified ΔP control

(3) Field Performance

At least 20% of field engines involve such survival system. While the load is cut off several times a year by lightning strikes or power failure, this system improvements ensure a virtually 100% survival rate.

<u>LNG Satellite Gas</u>

(1) Background

There are not large-scale oil and gas fields in Japan. The production output from small-scale fields accounts for less than 1% of domestic consumption. Accordingly, Japan depends on imports for most of its domestic consumption. For this reason, gas pipes are limited to coastal areas with LNG receiving facilities and major conurbations. Regions not connected to town gas pipes are still supplied from satellite facilities.

For cogeneration power generation plants in areas without gas pipes, LNG can be used by installing LNG tanks. Japan has an extensive road network, and the distances from LNG receiving facilities are relatively short, making power generation cheaper than purchasing commercial power supplies, even when relying on a supply system that makes frequent use of LNG tank trucks. This situation has led to an increasing number of power generating plants where LNG tanks have been installed.

(2) Technical Issues

With the LNG satellite supply system, the calorific value of the supply gas varies when the vaporizer starts up and with load and temperature fluctuations (see Figure 13). The increasing of heavier contents (propane and butane) within the vaporized gas raises the calorific value. Feeding fuel gas of this grade to the engine will cause abnormal combustion problems, e.g. knocking, affecting gas engine operations.

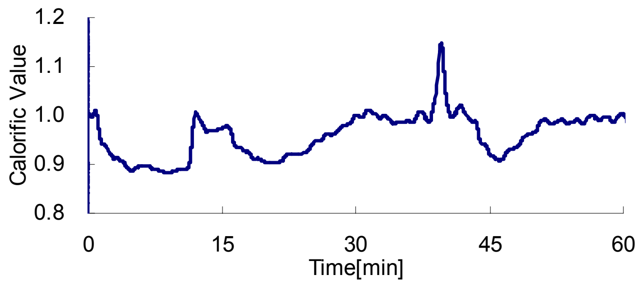

Figure 13 – Variation of calorific value

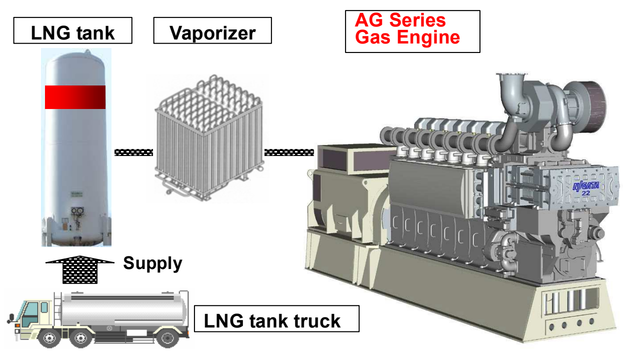

Figure 14 – LNG satellite facility

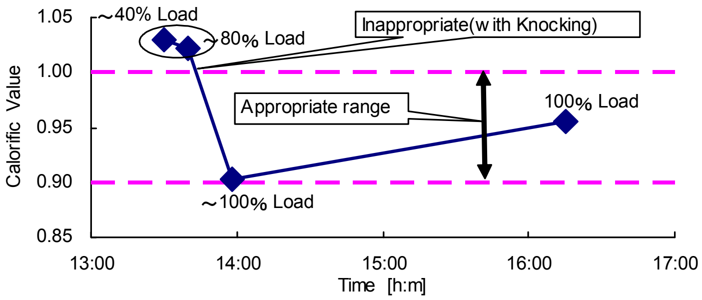

Figure 15 – Load operation and calorific value

Methods for minimizing calorific value fluctuations include modifying the vaporizing system at the LNG satellite facility and installing a large-capacity tank called a cushion drum. However, these facilities are in the scope of customer side, and may be minimal benefit for the manufacturers. Figure 14 shows a typical LNG satellite facility.

Figure 15 illustrates the actual fuel gas calorific value fluctuations confirmed in the field. The methane number is approximately 65 for a calorific value of 1.00. The amplitude of calorific value fluctuations deviates significantly from the ideal range.

In such case, the cogeneration systems are operated with higher excess air ratio from low to high load to ensure stable combustion, confirming the fuel gas calorific value fluctuation beforehand. Normally, operation with a high excess air ratio in the low load range will destabilize combustion. The powerful ignition source of the micro-pilot system allows stable operations without misfire. In some cases, a gentle transition is set for the time from low to rated load, depending on the actual conditions of calorific value fluctuations.

(3) Field Status and Discussions

Approximately 10% of facilities operated by 22AG engines use the LNG satellite supply system, maintaining stable operations through engine adjustments and appropriate measures. Figure 16 shows the operating status of a cogeneration plant with LNG satellite facility.

<u>Load Fluctuation Suitability</u>

(1) Background

The power generation system has alternative power control ways. One is a power generation constant control and another one is partial power control. The latter case is so called purchase power constant control.

The purchase power constant control is a method whereby the commercial power supply is kept constant and excess power demand is supplied with the engine output. Figure 17 shows a typical example of both applications.

The power generation constant control is used to run the engine at the most efficient rated load by minimizing use of the commercial power supply. The purchase power constant control is used to restrain the engine output if the power demand drops, since the commercial power supply may not exceed a preset value based on the supply contract concluded with the electric power company.

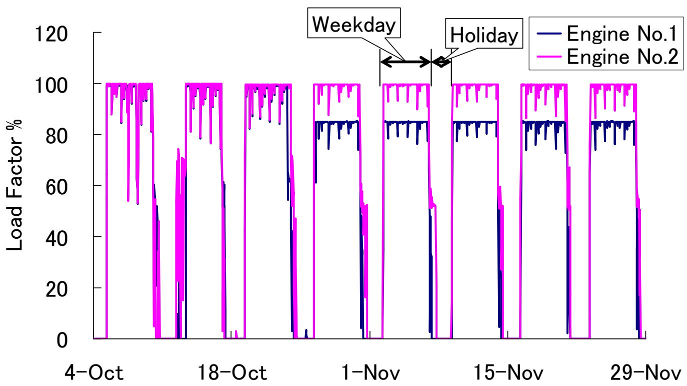

Figure 16 – Operation status of a plant with LNG satellite facility

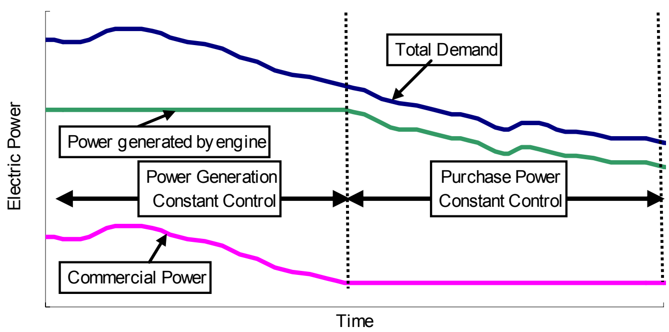

Figure 17 – Electric power control in a plant

(2) Technical Issues

The power generation constant control results in stable combustion when engine output is constant. However, engine output varies with purchase power constant control.

In the case of gas engines, the air-fuel ratio significantly affects combustion stability. If the load varies, the air-fuel ratio control will lag behind, resulting in unstable combustion. A particular problem occurs when the load increases rapidly, resulting in insufficient air, causing knocking. The control system has to respond fast, since load fluctuation with purchase power constant control depends on the fluctuation of the demand load. If the demand load drops below a preset load with purchase power constant control, the engine will stop. The engine starts again when the demand load rises above the preset load. This behavior increases the start-stop frequency. In the case of gas engines, air-fuel ratio control is often an issue at start-up; increasing the start-stop frequency raises concerns about start imperfection.

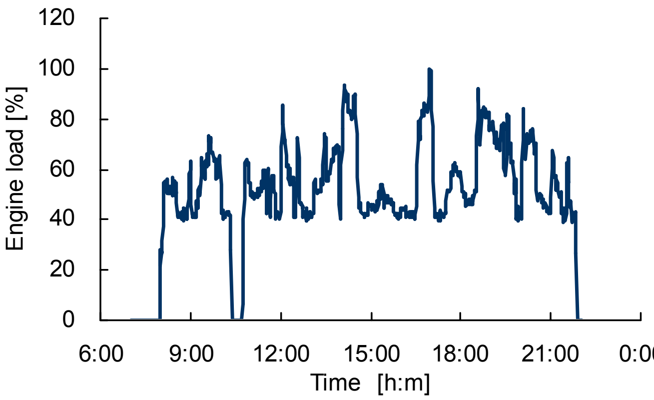

Figure 18 – Load fluctuations in one day

(3) Field Performance

Figure 18 shows controlled load fluctuations which are caused by electric demand of customers in actual field operations. However, the engine is running continuously to follow the load control requirement. To meet such frequent partial load operation, the excess air ratio will be set fairly high value, namely leaner mixture.

The ability to achieve stable combustion even at high excess air ratios is a major advantage of the micro-pilot system, which provides a powerful ignition source.

Figure 19 shows an example with the high start-stop frequency. Start and stop procedure is repeated 6 times in one day in this plant following the power demand. While the start-stop frequency is high, use of Niigata Power Systems' spark start system ensures reliable starting.

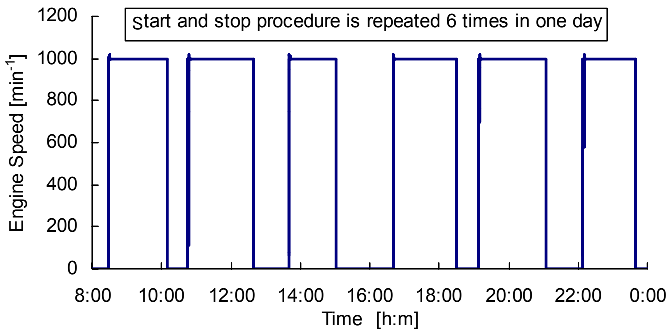

Figure 19 – High start-stop frequency

6MW CLASS GAS ENGINES

Two sets of 18V28AG have been delivered in 2008. These engines are used at a plant that retails electric power as power producers and suppliers (PPS). They run generally by the daily start and stop (DSS) operation.

Figure 20 shows the power output and thermal efficiency trends over a period of one year. Thermal efficiency also varies with load fluctuations, but initial efficiency at the time of delivery continues to be mostly maintained to this day.

This plant must be varied power output rapidly responding to demand every 5 minutes based on commands from consumers. Thus, the engines start and stop not only one time a day but also several times according to power demand. This operation corresponds to one of the examples mentioned in Figure 18 of load fluctuation suitability technologies. It also corresponds to the start-stop frequency described in Figure 19. Even under these conditions, the engine system continues to provide reliable service.

CONCLUSION

Due to the varied operating requirements, the gas engines used in Japan are subject to meet the rigorous conditions.

Niigata Power Systems has delivered more than 100 of versatile 22AG gas engines, proving their reliability under a wide range of operating conditions. With the addition of the 28AG to the lineup, the authors hope to meet future customer demand with a comprehensive range of output options.

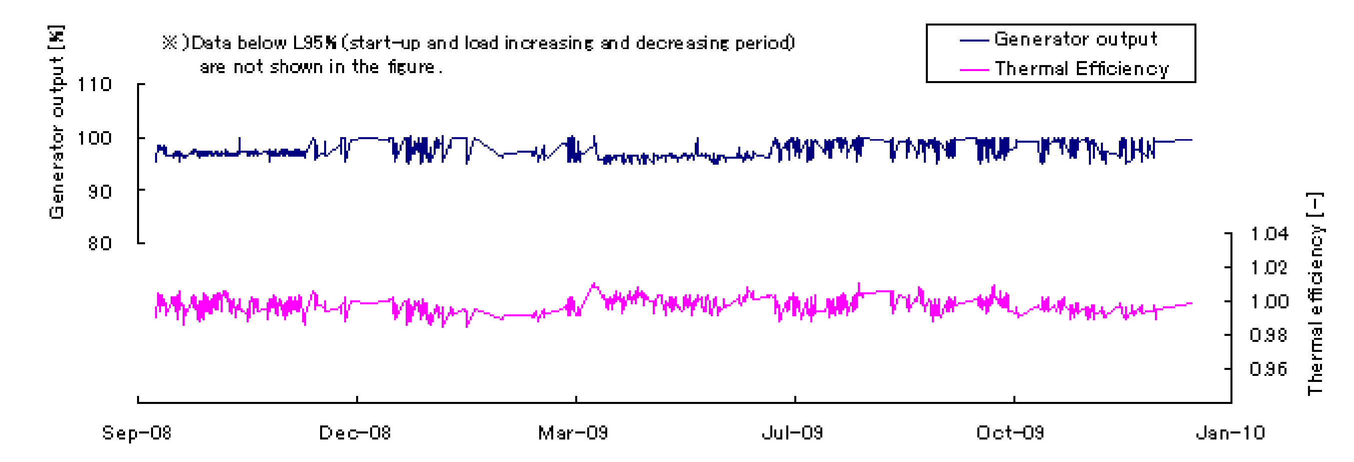

Figure 20 – One year trend of 28AG performance

The authors also hope to make use of the powerful ignition source which is the key feature of the micro-pilot compression ignition system and to achieve further improvements in output and efficiency.

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Fig. 1 – Cylinder head

Fig. 2 – Intake and exhaust Valves

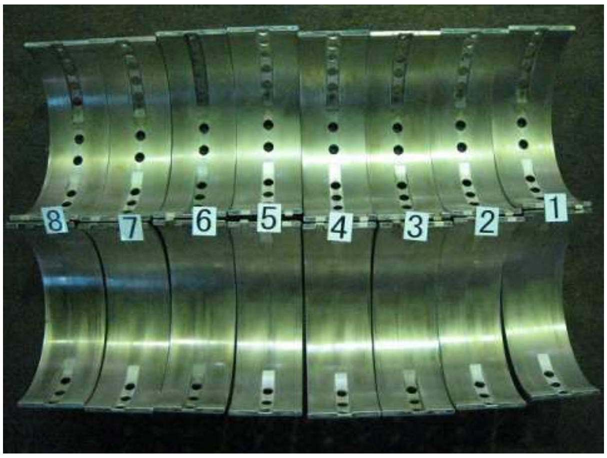

Fig. 3 – Crank pin bearings

Fig. 4 – Piston

Fig. 5 – Cylinder liner surface