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Flexible Operation of Gas Engines for Grid Power Stability and Carbon Neutrality

Operators Perspective

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ABSTRACT

In this study, Kawasaki Heavy Industries focused on the flexible operation method of gas engines as a technology to accelerate the transition to carbon neutrality and improve the stability of electric power supply against load fluctuation due to the increase of renewable energy. Kawasaki Heavy Industries' gas engines (KG series, KG-V series and KG-T series) have an output of 5 MW to 7.8 MW, and over 200 units have been ordered as of March 2024. In addition to the conventional KG and KG-V series, orders for the KG-18-T, which has an electrical efficiency of 51%, are steadily increasing due to its performance and reliability. They are widely used in thermal power plants with a total power generation capacity of 100 MW and cogeneration systems using waste heat recovery. In order to respond to “supply and demand adjustment market”, various technological innovations have been realized, such as an improvement of engine transient response and expansion of operating load range.

As for a lean-burn gas engine equipped with a turbocharger, when an attempt is made to improve the transient response, abnormal combustion occurs due to insufficient intake air pressure caused by turbo lag and fluctuation of the air-fuel ratio. We developed a rapid start-up system to reduce start-up time. The rapid start-up system is an integrated system to control load-up stabilization and to increase turbocharger responsiveness. The rapid start system was installed on the actual gas engine, and the start time was shortened.

In addition, in order to operate according to supply and demand adjustment market, there is a need for standby operation at the lowest possible load. By using the standby operation, engine output can increase more quickly than a stopped engine according to the increased demand for electricity. At low load operation, increase of oil up from engine lubricating oi and increase of unburned gas in exhaust gas are concerned.

In this paper, in order to solve these issues, we introduce the newly developed technologies and the actual operation results and discuss the results to make the gas engine operate more flexibly. In addition, we introduce the operation example utilizing high performance and flexible functions of our KG gas engines.

1 INTRODUCTION

In this study, Kawasaki Heavy Industries (KHI) focused on the flexible operation method of gas engine as a technology to accelerate the transition to carbon neutrality and improve the stability of electric power supply against load fluctuation due to the increase of renewable energy.

In order to stabilize the grid frequency, it is necessary to make the amount of generated power equal to the power demand. Generally, as shown in Figure 1, there are “base load” that outputs a nearly constant amount of power, “renewable energy” such as solar and wind power that have large output fluctuations, and “thermal power” that are easy to adjust output. By controlling the output of thermal power, the amount of total power can be adjusted to match the power demand. In landscape application, the need to operate gas engines as a backup for solar and wind power is increasing. Accordingly, it is becoming more common to operate gas engines flexibly. For example, as shown in Figure 2, one operation method is to start up the gas engine in the morning and operate it at a high load, then reduce the gas engine output after the solar power output starts to rise, operating with as a low load as possible during the day. After the solar power output drops in the evening, operating it at a high load again, and then stop operation depending on the demand on the grid. In this way, gas engines are expected to contribute to grid stabilization, promote the expansion of renewable energy, and accelerate the transition to carbon neutrality.

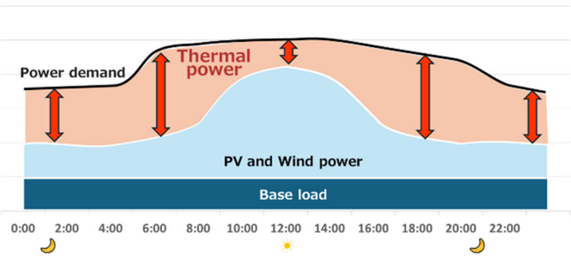

Figure 1. Image of power demand and power generation adjustment

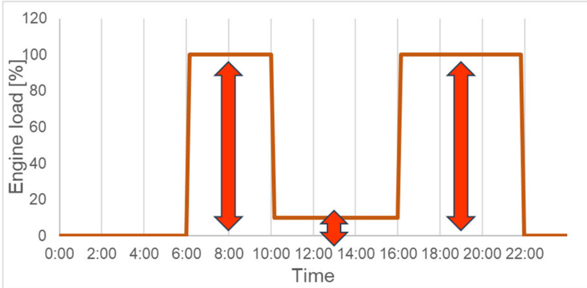

Figure 2. Image of gas engine operation for grid stabilization

Kawasaki Heavy Industries' gas engines (KG series, KG-V series and KG-T series) have an output of 5 MW to 7.8 MW and over 200 units have been ordered in Japan and overseas as of March 2024. For an example, the whole view of 110MW class power plant “Mobara Power Station” that KHI delivered is shown in Figure 3 and the gas engines installed in the plant are shown in Figure 4.

Figure 3. The whole view of 110MW power plant

Figure 4. The generator room of 110MW power plant

In addition to the conventional KG series, orders for the KG-18-T, which has an electrical efficiency of 51%, are steadily increasing due to its performance and reliability. They are widely used in thermal power plants with a total power generation capacity of 100 MW class and cogeneration systems using waste heat recovery.

In order to respond to “Supply and demand adjustment market”, various technological innovations have been realized, such as improvement of engine transient response, expansion of operating load range.

In Japan, thermal power generation, including gas engines, is also expected to play a role as an adjusting power to compensate for fluctuations in renewable energy output. In fact, market trading in all categories in “Supply and demand adjustment market” have begun since April 2024. Generally, the category in which gas engines enter is “Replacement Reserve” of 15-minutes response. In this study, various technical improvements were made to the gas engines so that they could participate to “Frequency Restoration Reserve” of 5-minutes response. In Japan, as well as in other major countries, the response time for each category is set at approximately 15-minutes to 5-minutes. For this reason, 5-minutes response is one benchmark for meeting the needs of “Supply and demand adjustment market” worldwide.

In order to operate gas engines according to “supply and demand adjustment market”, there is a need for standby operation at the lowest possible load. By using the standby operation, engine output can increase more quickly than a stopped engine according to the increased power demand. At low load operation, increase of oil up from engine lubricating oil and increase of unburned gas in exhaust gas are concerned.

To solve these issues, we introduce the newly developed technologies and the actual operation results and discuss the results to make the gas engine operate more flexibly. In addition, we also introduce the operation example utilizing high performance and flexible functions of our gas engine.

2 KAWASAKI GREEN GAS ENGINE

The history of electric efficiency of “Kawasaki Green Gas Engine” is shown in Figure 5. KHI launched KG gas engine (KG series) to the market in 2007 and developed KG-V series of electrical efficiency 49.5% in 2010. After that, KG-18-T engine which improved electrical efficiency to 51.0% was released in 2020. Main particulars of KG gas engines are shown in Table 1. The KG gas engines cover an electric output range of 5 to 7.8 MW class. The conventional KG series and KG-V series have an electric efficiency of 48.5 to 49.5%, and the latest KG-T type engine has an electric efficiency of 51.0%. KG series are suitable for cogeneration systems that utilize the waste heat recovery, and KG-T engine is suitable for thermal power plants thanks to higher electric efficiency.

KG gas engines also have other features such as short start-up time and wide operating range. These indicators are important for customers to operate gas engines flexibly and contribute to stabilizing the grid. We are developing the technologies to improve overall performance, including these indicators, and introduce the technologies in this paper.

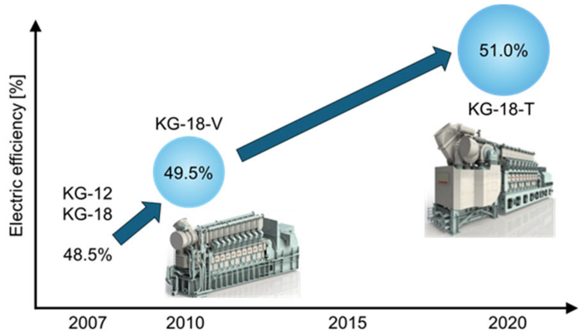

Figure 5. History of electric efficiency of KG gas engines

Table 1. Main particulars of KG gas engines

Engine Model	KG-12	KG-18	KG-18-V	KG-18-T
Electric output [kW]	5200 / 5000	7800 / 7500		
Electric efficiency	48.5%		49.5%	51.0%
Speed [rpm]	750 / 720			
Frequency [Hz]	50 / 60			
No. of Cylinders	12	18		
Bore [mm]	300			
Stroke [mm]	480			
Start-up time	Standard: 10 minutes Option: 5 minutes			
Operating range	20-100% load			

3 TRANSIENT RESPONSE

As for a lean-burn gas engine, when trying to speed up the transient response, abnormal combustion occurs due to fluctuation of the air-fuel ratio. For this reason, there is a limit to shorten the start-up time.

We developed rapid start-up system to reduce start-up time. The rapid start-up system is an integrated system to control load-up stabilization and to increase turbocharger responsiveness. The engine load-up stabilization control was developed to enable stable operation even when the air-fuel ratio fluctuates. We introduce the rapid start-up system that applies these technologies in detail and show the test results on the actual gas engine.

3.1 Rapid start-up system

Regarding abnormal combustion, when the air-fuel ratio is too low, knocking occurs, and when the air-fuel ratio is too high, misfire occurs as shown in Figure 6. When the engine load is increased slowly, the air-fuel ratio can be easily controlled within the normal operating range. However, more rapid load-up causes abnormal combustion, due to imbalance of the air-fuel ratio. When engine load is increasing, intake air pressure tends to be lower than the required value. In other words, the air-fuel ratio drops and knocking becomes more likely to occur. To improve transient response performance, we developed and applied combustion control and intake air pressure control that improve knocking resistance. For example, the ignition timing and intake air temperature were optimized to enable stable combustion and operation even at lower intake air pressure at whole engine load. By applying the load-up stabilization control, abnormal combustion such as knocking was prevented from occurring even during rapid start-up.

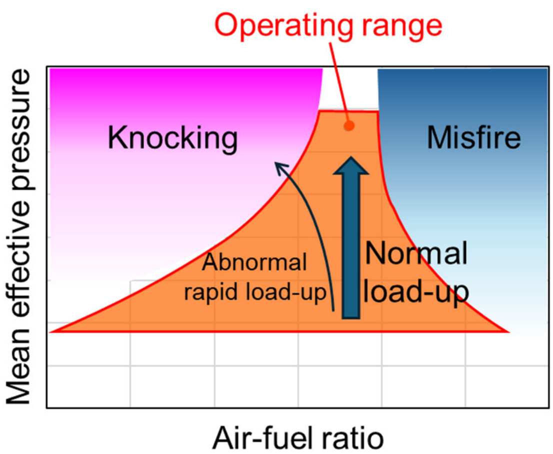

Figure 6. Relationship between air-fuel ratio and abnormal combustion

The external dimensions of the engine are the same as standard type and the only difference point is that an additional pipe is installed to supply compressed air. The rapid start-up system images with compressed air are shown in Figure 7 and the picture of compressed air pipe and solenoid valve is shown in Figure 8. The compressed air piping consists of air reservoir, solenoid valves, and an orifice. The responsiveness of turbocharger is improved by injecting compressed air and assisting the turbocharger speed. The compressed air is used after reducing the pressure of starting air to appropriate value through the orifice. The compressed air is also controlled by the solenoid valve to inject at appropriate timing based on the deviation between the planned and measured intake air pressure. The supply of compressed air is optimized according to the engine load and the combustion condition, and thereby minimizing the air consumption. By improving the hardware aspect of the turbocharger responsiveness, we have improved the responsiveness of the intake air pressure to engine load, resulting in more stable air-fuel ratio.

In terms of hardware modifications, the rapid start-up system has simple and easy structure. It is easily retrofitted to existing engines and sites from the standard specification to the rapid start-up system by modifying the piping.

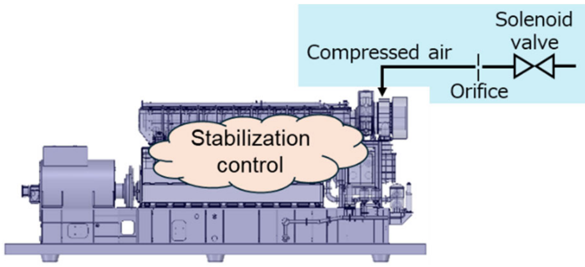

Figure 7. Rapid start-up system images of software and hardware

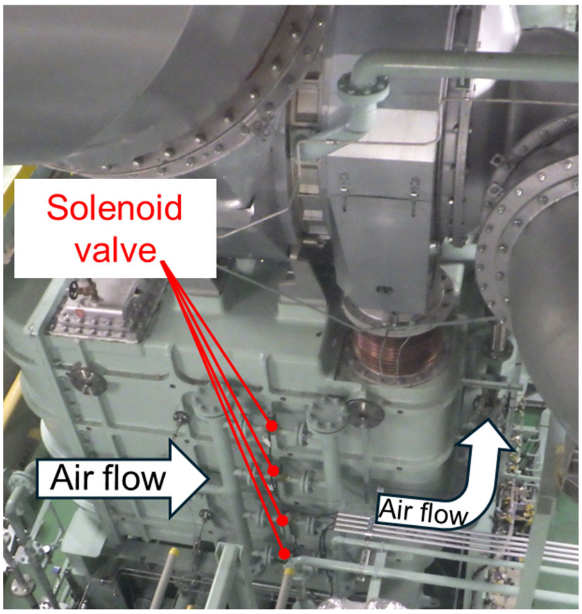

Figure 8. Picture of compressed air pipe

In this way, the rapid start-up system can improve the transient response of gas engine with only simple modifications to the hardware and software. Therefore, it is easy to install not only for new construction, but also for retrofitting existing gas engine. In fact, we retrofitted our gas engine equipment that supplies electricity to our Kobe factory. And we carried out the long-term verification test of rapid start-up, which we will introduce in the next section.

3.2 Test results

KHI have an actual engine in our factory, as shown in Figure 9. The gas engine is KG-18-T type, which supplies electricity to Kobe factory every day and is operated under Daily Start and Stop (DSS). The rapid start-up system has been applied to this engine, and the engine has been starting up every morning using the rapid start-up system. The rapid start-up system has been performed more than 400 times in total, averaging more than 100 times per year, and it has been confirmed that all the operations have been stable without any trouble such as abnormal combustion for now.

Figure 9. Kobe Power Center Unit 4 power plant

As another example, we applied the rapid start-up system to KG gas engine and conducted the verification test. Figure 10 shows the test results of normal start-up and rapid start-up after grid connection to reaching 100% engine load. During normal start-up, it takes approximately 400 seconds to reach 100% engine load, but in case of rapid start-up, engine output can be increased to 100% in approximately 100 seconds. The injection of compressed air is limited to the short period when the turbocharger is not rotating much at the low load range. Thanks to the short period injection of compressed air, the intake air pressure is increased to a sufficient level. And the load-up stabilization control was working properly during load-up, and 100% load was reached without any abnormal combustion.

The test results show that it is possible to achieve 100% load within 3 minutes, when evaluated from the start command to reaching 100% engine load. The rapid start-up system can be easily used for flexible operation as a backup for renewable energy. Regarding flexible operation, details are described in Section 5.

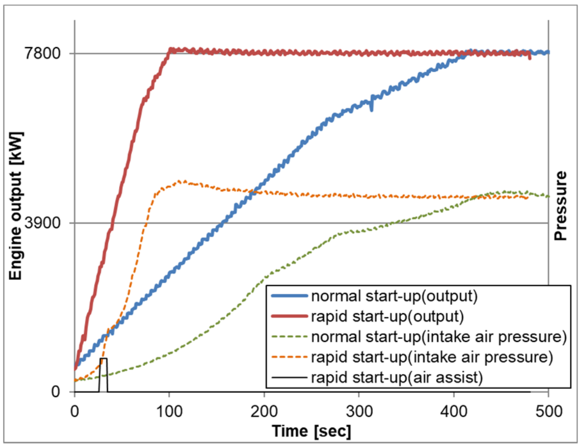

Figure 10. Test results of rapid start-up

3.3 Reliability of rapid start-up

We also evaluated the reliability of engine components against rapid start-up. The combustion chamber is the part that is affected by combustion due to rapid start. The part of the combustion chamber most affected by heat is cylinder cover, therefore we confirmed the impact on reliability. The temperature of the cylinder cover was measured during the rapid start-up test and normal operation. The temperature difference between the explosion surface and the cooling side position about 40mm behind is shown in Figure 11. It found that the temperature difference, i.e., thermal stress, increases more quickly during the rapid start-up than normal start-up. However, the maximum transient temperature difference is lower than the level during steady state operation at 100% load, because ignition is advanced during steady-state operation at 100% load and the engine is operated at higher Pmax than during start-up, resulting in a more severe thermal environment at 100% engine load. Therefore, we confirmed that there is no concerns about reliability during the rapid start-up.

Based on the measurement results, the temperature distribution and transient thermal stress distribution were analyzed. The analysis results of the temperature distribution are shown in Figure 12. The upper left figure shows the transient temperature distribution at low load in the initial stage during the rapid start-up. The upper right figure shows it at part load after a short period of time has passed, and the bottom left figure shows it at high load at the late stage of the rapid start-up. High temperature area is observed in part of the surface of the explosion surface at initial stage. The range of high temperature on the explosion surface expands slightly over time, and the temperature of exhaust gas port is increasing slowly. The temperature of the entire cylinder cover is almost the same level as the part load results. The bottom right figure shows the results when a steady state is reached under 100% engine load after a significant amount of time has passed. The temperature is the highest value on the entire cylinder cover, especially near the exhaust gas port. From these results, we evaluated that the effect of heating the cylinder cover due to rapid start-up is limited to the explosion surface area of the cylinder cover at beginning of stat-up, because the rate of temperature rise is sufficiently slow except for the explosion surface area. As for the reliability of the explosion surface during the rapid start-up, it has already been confirmed in Figure 11 that is no concerns.

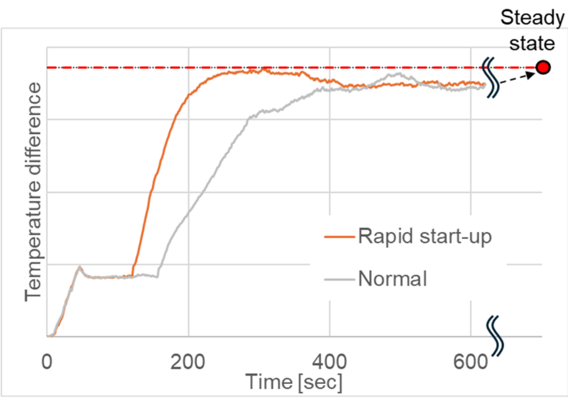

Figure 11. Temperature measurement results

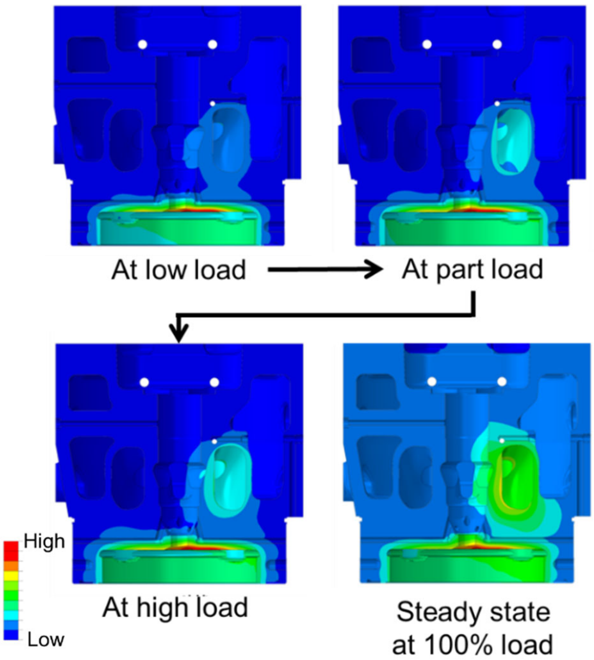

Figure 12. Analysis results of the temperature distribution of cylinder cover

3.4 Load reduction test results

Regarding the improvement of the transient response performance of gas engine, a lot of attention is focused on insufficient intake air pressure during load-up. However, there are also issues such as misfire and turbocharger surging during rapid load reduction. Turbocharger surging is a phenomenon in which the pressure of compressed air pushed out by the turbocharger's blower is defeated by the intake air pressure at the discharge side, causing the compressed air to flow backwards. When surging occurs, the turbocharger generates severe vibration and noise, and the gas engine intake air pressure pulsates abnormally. In the worst case, turbocharger surging can lead to the engine emergency trip due to the excessive combustion pressure.

As countermeasure against turbocharger surging during the rapid load reduction, the rapid load reduction system was developed that uses the exhaust gas bypass valve to rapidly decrease the turbocharger speed and the intake air pressure. As the rapid load reduction test, the engine load was rapidly reduced from 100% engine load. The test results are shown in Figure 13. The engine load can be reduced from 100% load to no load in about 60 seconds. The load reduction rate is set at 80%/min. During load reduction, the rapid load reduction system is activated, and the intake air pressure is rapidly decreased by rapidly opening the exhaust bypass valve. Figure 14 shows the valuation results of turbocharger surging margin. This graph means that surging occurs when the air flow and pressure ratio fall to the left side of the red solid surging line. Even during rapid load reduction, the measurement results show that the intake air pressure is decreased stably, staying to the right side of the surging line without approaching the surging line.

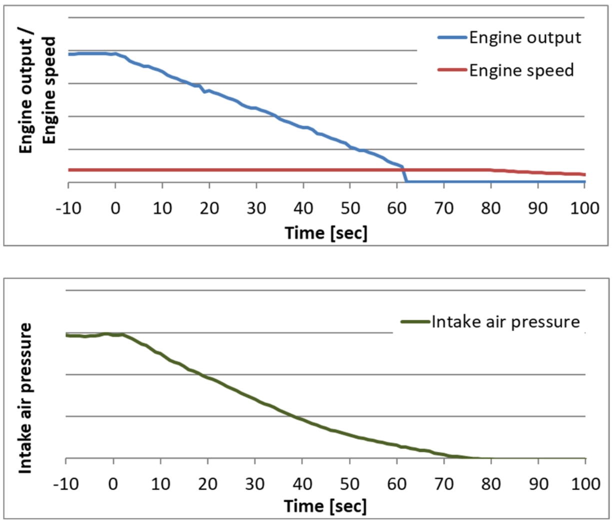

Figure 13. Test results of rapid load reduction

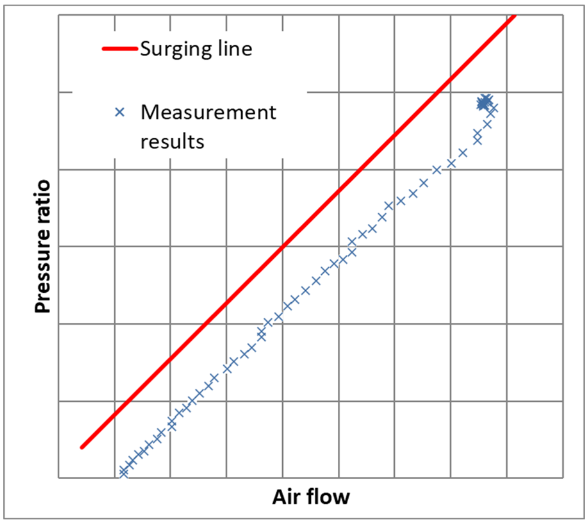

Figure 14. Evaluation results of surging margin

This rapid load reduction system has also been applied to the Kobe Power Center Unit 4 power plant and has been used in actual operation over 5 years, with a proven track record of trouble-free and stable operation.

By applying rapid start-up and rapid load reduction technologies to gas engines, the transient response can be improved so that the engine output follows even a sudden change in power demand on the grid side, as shown in Figure 15. Even a single KG gas engine can cover large electric power fluctuations of several thousand kW and contribute to stabilize the power grid against renewable energy.

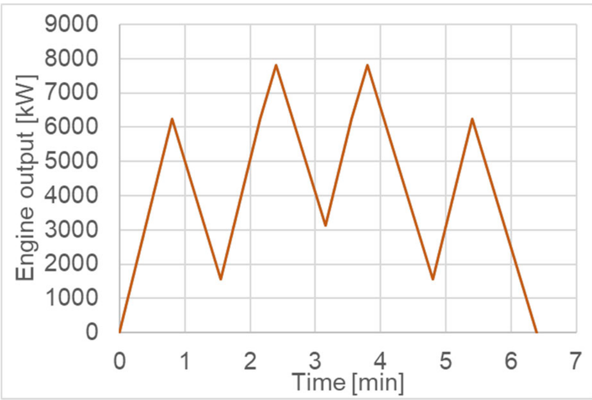

Figure 15. Improved transient response

4 STANDBY OPERATION

In operating gas engines to meet the "Supply and demand adjustment market", there is a growing need to usually operate gas engines at the lowest possible engine load, in order to be able to suddenly increase the engine load to meet the electricity demand when renewable energy output falls. When gas engine is operated at low load, the combustion temperature is low, and it makes the combustion unstable and increases the frequency of misfire. In addition, the sealing performance of the piston rings decreases at low engine load, the amount of lubricating oil increases, and then it causes the inside of the combustion chamber to become dirty. These lubricating oil-up and fouling in the combustion chamber make the combustion more unstable. Furthermore, unburned gas is generated in the crevice volume, which is the narrow space between the piston top land and the cylinder liner, and this has a relatively larger effect at lower engine load. Thus, in standby operation, it is necessary to overcome the issue of increased unburned gas in addition to unstable combustion.

4.1 Technologies for standby operation

As shown in Figure 16, KG gas engine has a combustion chamber design of pre-chamber type and has a main combustion chamber and a pre-chamber with independent structures. The amount of fuel gas injected into the main combustion chamber is adjusted using a main chamber solenoid gas admission valve, and the amount of fuel gas injected into the pre-chamber is adjusted using a solenoid valve for pre-chamber. And the intake air pressure is controlled by the exhaust gas bypass valve. Thanks to this configuration, the air-fuel ratio in the main combustion chamber and in the pre-chamber can be adjusted independently. By tuning these combustion adjustment parameters for low engine load, standby operation was achieved. Furthermore, the control of the cooling water system of the intake air temperature was also optimized, because the intake air temperature also affects the air-fuel ratio.

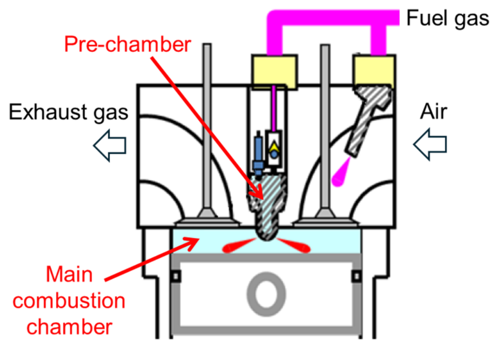

Figure 16. Schematic diagram of main combustion chamber and pre-chamber

4.2 Test results of standby operation

The fouling in the combustion chamber caused by lubricating oil-up can be cleaned up by increasing the engine load and raising the temperature in the combustion chamber. Using actual engines, we verified the accumulation of lubricating oil-up and the frequency of abnormal combustion.

In the first case, after operating at 20% engine load for accumulative 21 hours, the engine load was increased rapidly and clean-up operation in the combustion chamber was performed at high engine load for more than an hour. During the low load operation, the rapid load-up, and the clean-up operation, smooth operation was continued without any abnormal combustion. The frequency of misfire was reduced by optimization of engine tuning at low load. After the verification test, an inspection of the combustion chamber was carried out using a borescope, and it was confirmed that the engine was in good condition.

Next, as shown in Figure 17, after operating at 20% load for accumulative 30 hours, the engine was stopped and the combustion chamber such as piston were disassembled and visually inspected. The operation was conducted smoothly without any trouble. As a result of the engine overhaul inspection, a picture of the piston is shown in Figure 18. It was confirmed that both the piston and the combustion chamber were in good condition, with no sign of lubricating oil-up.

From the results of these two tests, the time during which standby operation can be continued and the operating mode for low load operation were determined. We have applied the standby operation to the Kobe Power Center Unit 4 power plant for over three years, and we have confirmed that all operations, including low-load operation and load-up, can be performed smoothly without any abnormal combustion.

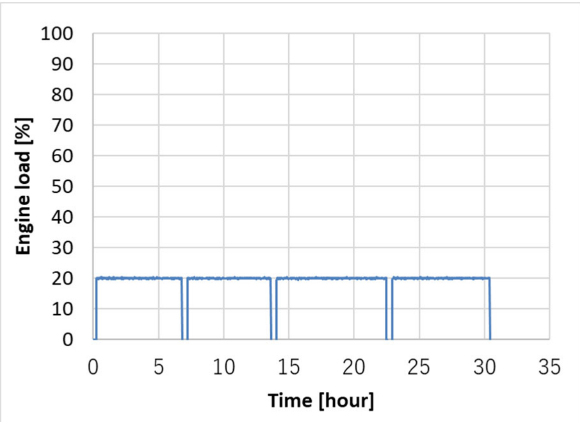

Figure 17. Standby operation time

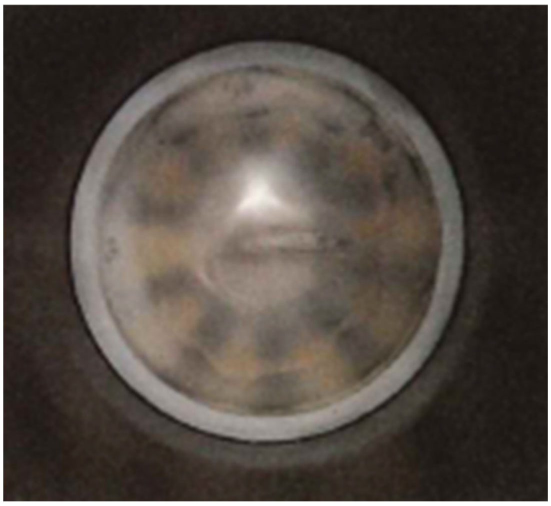

Figure 18. Picture of dismantled piston crown

4.3 Test results of ultra low load operation

In the ultra low load operation of 10% engine load, the emission of larger amount of unburned gas becomes a major issue. In this load range, the verification test was conducted to reduce unburned gas by intermittent injection. The intermittent injection is a method of injecting fuel gas once a few cycles, rather than every cycle, to balance the air-fuel ratio and strengthen combustion. The test results of comparing normal operation and intermittent injection are shown in Figure 19. Compared to normal operation, intermittent injection reduced the amount of unburned gas in the exhaust gas by approximately 85%. By utilizing intermittent injection in this way, it was confirmed that the amount of unburned gas is significantly reduced, and stable operation of ultra low load is possible.

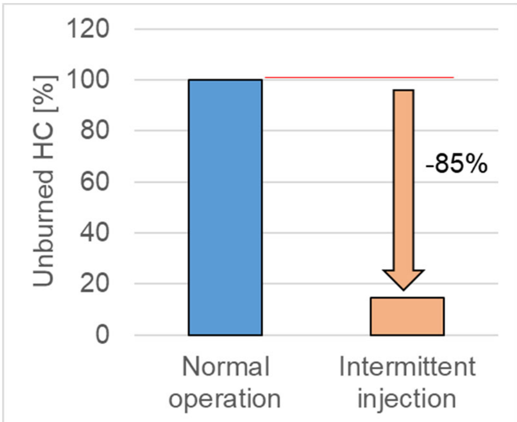

Figure 19. Unburned HC measurement results

The engine behavior of switching from ultra low load operation of intermittent injection to normal has also been verified. When increasing engine output from 10% engine load, if the injection method is changed from intermittent injection in step, engine output suddenly rises, and engine load fluctuation occurs. Therefore, to prevent the engine load fluctuation, we adopted the method of gradually transitioning from intermittent injection to normal operation while adjusting the injection amount of fuel gas. Thanks to this countermeasure, it was confirmed that the engine could be operated smoothly even when switching the injection method and engine load as shown in Figure 20. After approximately 1 hour of standby operation, the engine load was increased and normal operation was carried out, and it was found that there were no abnormal fluctuations of the engine load.

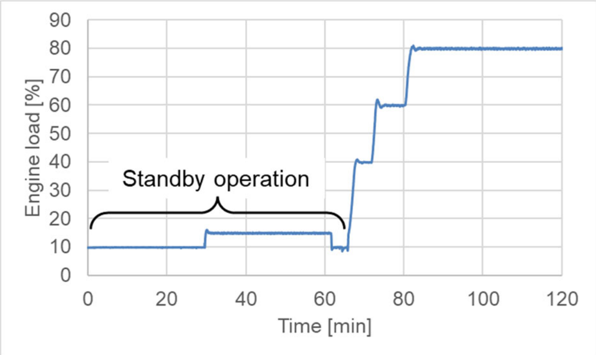

Figure 20. Standby operation and load-up

As for reducing the engine load, switching from normal operation to intermittent injection also causes a sudden drop of engine output. We separately optimized the injection amount when the engine output is increased and decreased. In this way, we verified that KG gas engine can be operated stably in ultra low load operation, including transitions to high engine load.

5 PROPOSAL OF FLEXIBLE OPERATION

By using the improved technologies in this study, it is possible to meet the flexible operation needs of gas engines as shown in Figure 2 in Section 1. Furthermore, it is possible to consider more flexible operation than conventional engines, as shown in Figure 21. It is found that the flexibility of engine operation is improved compared to conventional engines, in terms of shorter start-up time, shorter load reduction time, standby operation at lower engine load, shorter load increase time, and shorter engine stop time.

Regarding the gas engine start-up process, normally, after the start command is pressed, a fuel gas leak check is performed, the engine speed is increased to rated speed, the engine is connected to the grid, and then engine load can begin to increase. Even including all these processes, it is possible to achieve 3 minutes start-up from the start command to reaching 100% engine load. The load reduction rate and the minimum load for standby operation have also been improved and it makes gas engines operate flexibly according to the operating status of renewable energy.

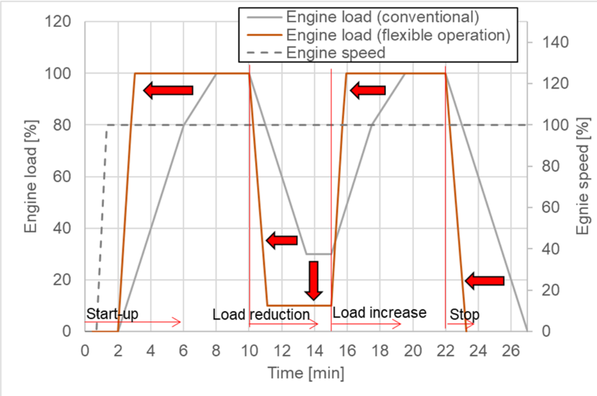

Figure 21. Time chart of flexible operation

As results of this study, the improvements are shown in Table 2. Significant improvements in flexibility operation were confirmed in start-up, load increase, load reduction, and standby operation. Thanks to these specifications, KG gas engine can participate to “Frequency Restoration Reserve” of 5-minutes response and expand the ways of gas engines operation.

Table 2. Comparison between flexible operation and conventional specification

	Flexible Operation	Conventional	Improvement results
Start-up	3min	10min	7min shorter
Load increase	100%/min (Fastest)	20%/min	210sec shorter from min. load to 100% load
Load reduction	80%/min	20%/min	140sec shorter from 100% load to min. load
Standby	10% load	30% load	20% expansion

6 CONCLUSIONS

KHI developed the technologies for flexible operation of gas engines to stabilize the grid even in the era of widespread use of renewable energy and to accelerate the transition to carbon neutrality. KHI introduced the improved transient response and the standby operation, including the actual test results. By utilizing these technologies, KHI has proposed a new way of operating gas engines as a backup for renewable energy.

KHI continues to develop gas engine technologies with the aim of achieving carbon neutrality.

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