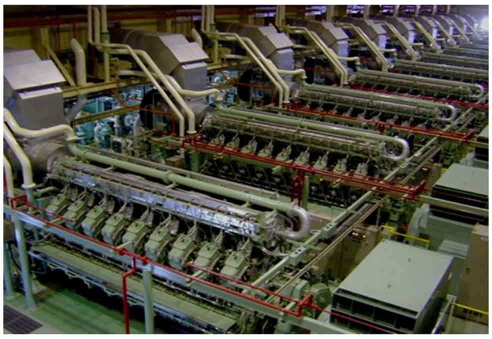
Technologies for Improving Power Generation Efficiency and Utilizing the Cooling Water Energy of the KU30GSI Gas Engine for Power Generation



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Against the backdrop of the reduction of environmental impact and the development of shale gas, natural gas resources have attracted a great deal of attention as a primary fuel for the future. In its product lineup, Mitsubishi Heavy Industries Engine and Turbocharger, Ltd. (MHIET) offers a high-speed GSR gas engine covering 305 to 1,500kW and the mid-speed KU30GSI model covering 3,650 to 5,750kW, both of which are applicable to small-scale distributed power generation, co-generation in facilities or plants and dedicated utility power generation. This paper will describe the technology for increased efficiency of the KU30GSI-Plus model, which achieved power generating efficiency of 49.5%, and technologies relating to the all-steam recovery system that is designed to utilize the engine cooling water by raising its temperature so that it could be used as a heat source for steam recovery.

1. Introduction

Natural gas resources have attracted attention as a future primary fuel due to the increased need for the reduction of environmental impact and an alternative to oil. On the other hand, interest in distributed power sources, which are quite useful in times of disaster, is expected to grow further.

Under such circumstances, gas engines, due to their excellent startup performance, load following capability and flexible applicability to waste heat recovery, are utilized for various applications including Combined Heat and Power (CHP) generation with a wide range of power output. In particular, mid-speed gas engines have achieved excellent power generation efficiency, a quick startup within 10 minutes and high-efficiency waste heat regeneration utilizing high-temperature exhaust gas, which resulted in a total efficiency of over 80%. MHIET regards our mid-speed gas engines as one of the best choices for providing high-efficiency energy solutions.

MHIET's KU gas engine series models include the micro pilot-ignited KU30GA (MACH-30G) brought to the market in 2002, which is based on the spark-ignited KU30G gas engine released in 1990, but is further sophisticated in terms of its power output, efficiency and endurance. The KU30GA was highly evaluated for its high reliability and performance and more than 150 units were sold.

In 2009, based on the KU30GA engine with its extensive track record, MHIET adopted the spark-ignition method and released the KU30GSI gas engine (total efficiency-focused model) on the market. The product focused on overall efficiency including waste-heat regeneration and had excellent compatibility with a wide range of applications.

Furthermore, in 2012, in order to meet increased customer needs for power generating efficiency, MHIET released the KU30GSI-Plus gas engine (power generation efficiency-focused model), adding a new model in our product lineup that would satisfy a wide range of needs for

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overall efficiency and power generating efficiency.[1, 2] The power generating efficiency has been further improved in the KU30GSI-Plus engine. In 2015, the same model with an increased efficiency of 49.5% was released.[3, 4]

Meanwhile, MHIET successfully commercialized an all-steam recovery system that collects steam even from warm waste water, which has not been utilized effectively until now, from non-utility generation facilities in Japan, as a system product jointly developed with 3 other entities* in May 2015, with the top "power generation + steam recovery" combined efficiency achieving 71.1%.

This paper will describe the excellent features of the KU30GSI gas engine and its technologies for improved power generating efficiency, as well as those for the extensive utilization of waste heat as typified by the all-steam recovery system (technologies utilizing energy from cooling water).

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2. Overview of KU gas engine

The four stroke-cycle KU30GSI model pre-chamber lean-burn gas engine with spark ignition is equipped with 12 to 18 cylinders and covers power output of 3,650 to 5,750kW. **Table 1** illustrates the principal specifications of the KU30GSI and KU30GSI-Plus engines.

Table 1 Principle specifications

Engine type		KU30GSI	KU30GSI-Plus
Number of cylinders		12－18	
Bore/Stroke	mm	300×380	
Speed	min^{-1}	720/750	
Generator output*	kW	3650－5750	
Generation efficiency*	%	46.5	49.5
NO_X (O_2=0%)	ppm	< 320	
Engine mass	kg	40000－60000	

*The table above is based on the ISO3046 conditions and MHIET-recommended standard gas.

The total efficiency-focused KU30GSI model has achieved improved power generating efficiency and high exhaust gas temperature at the same time, realizing the top-class total efficiency of over 80% compared with similar output gas engines, including power generating efficiency of 46.5%, exhaust gas temperature of 395°C, NOx emissions of 320ppm (at 0% O_2), making it most suitable for applications combined with exhaust heat regeneration such as CHP generation.

Furthermore, MHIET developed the power generating efficiency-focused KU30GSI-Plus model with enhanced power generating efficiency applicable to dedicated utility power generation and Independent Power Producers (IPP). In 2015, the same model with improved power generating efficiency of 49.5% (including power necessary for lubricating oil pump on engine) was launched on the market.

The KU30GSI series models are utilized for various applications both at domestic and abroad, achieving field operating hours of approximately 30,000 hours. The KU series gas engines as a whole has achieved a total of more than 7 million operating hours. The KU30GSI is a highly-reliable gas engine which has 80% of its parts in common with other KU series models. From the planning stage, the design was oriented to facilitating ease of access to installation, wiring, plumbing, etc. Thus, the streamlining of on-site installation and a shortened work period for the construction of power plants are targeted.

3. High-efficiency gas engine power generating technology

In recent years, due to the application of the Miller cycle and improved technologies for in-cylinder flow prediction utilizing Computational Fluid Dynamics (CFD), the power generating efficiency of gas engines has been rapidly advancing. MHIET has been working hard on the further improvement of power generating efficiency while securing combustion stability, being very aware of the Japan-specific gas properties (methane number 65).

3.1 Advanced Miller cycle

Upon the application of the advanced Miller cycle, we first confirmed the in-cylinder pressure fluctuation and the impact that the timing of when the intake valve is closed would have on the thermal efficiency. **Figure 1** demonstrates a comparison between Case A and Case B with late intake valve closing timing, in both of which the air excess ratio and in-cylinder pressure are maintained at a certain level. In Case A, Coefficient of Variation (COV) Pmax, indicating the range of the maximum in-cylinder pressure fluctuation, improves by about 50% compared with Case B, and the thermal efficiency increases by about 1pt%. In Case A, although the intake valve opens early and there is an increased period of time when the intake and exhaust valves are both open, allowing unburnt gas to blow through, which might lead to a possible decrease in the thermal efficiency, the combustion stability realizes improved thermal efficiency. **Figure 2** shows the time-series behavior of the peak firing pressure in both Cases A and B. There are the larger fluctuation with frequent high peak pressure events in Case B, whereas Case A demonstrates excellent combustion stability.

According to the test results above, the KU30GSI-Plus engine is optimized based on Case A, where the intake valve closes early in order to achieve combustion stability. Such an optimization focusing on reliability prevents excess temperature rise in the parts and components inside the combustion chamber induced by knocking and other factors originating from unstable combustion. It also contributes to an increased service life and long-term improved reliability of parts and components, as well as allowing the gas engines to achieve sufficient reliability to changes in environmental conditions including load variation and temperature fluctuation of the cooling water. The KU30GSI-Plus model engine achieves stable combustion, quick startup performance and excellent in particular load following capability even during transitional periods when loads are increasing/decreasing.

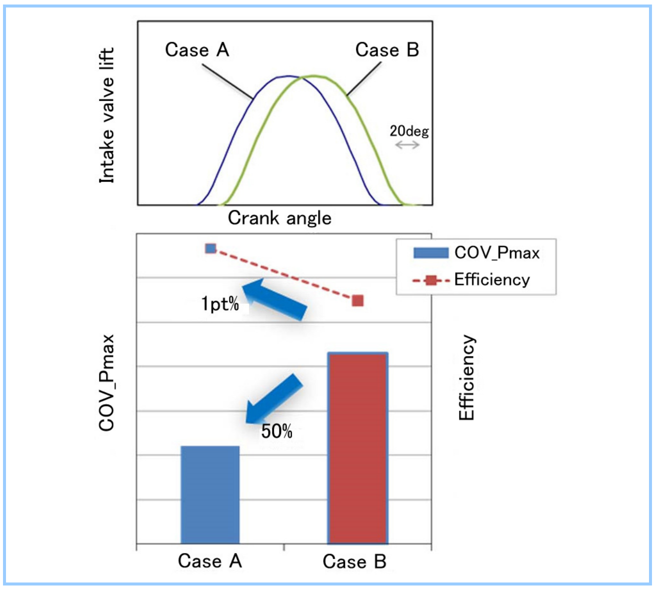

Figure 1 Miller timing effect

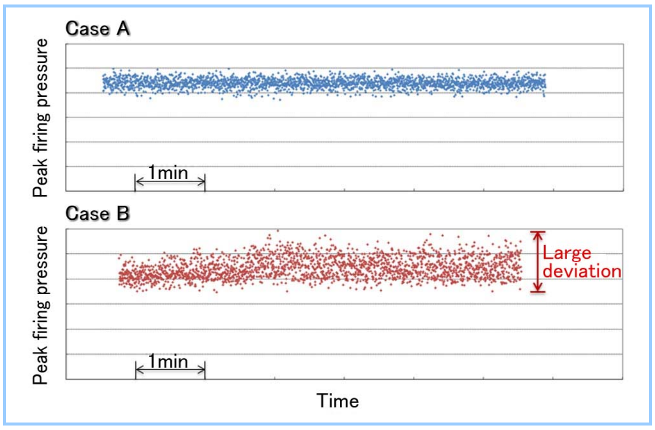

Figure 2 Peak firing pressure based on miller timing

3.2 Enhancement of turbocharger efficiency

In order to achieve high efficiency in Case A, where the intake valve closes early, it is necessary to maintain high turbocharger efficiency when the pressure ratio increases. The KU30GSI-Plus model adopts MHI's high-efficiency MET42MB Turbocharger with the maximum pressure ratio of 5.0. **Figure 3** illustrates a cross-section of the MET42MB Turbocharger, whereas **Figure 4** demonstrates a comparison in efficiency before and after changes of specifications when engine operated. In order to maximize the efficiency of the turbocharger, the specifications and characteristics are carefully selected and combined so that the turbocharger efficiency is improved by about 2pt% in a high-pressure ratio region of 4.5 and over, which contributes greatly to the improved power generating efficiency of the KU30GSI-Plus engine.

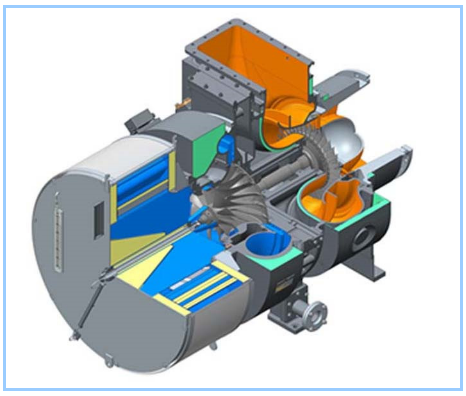

Figure 3 MET42MB Turbocharger

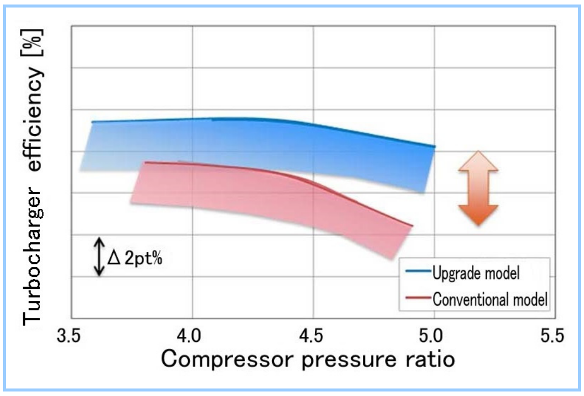

Figure 4 Increased turbocharger efficiency

3.3 Further reduction of dead volume areas

For the KU30GSI-Plus model, the occurrence of abnormal combustion and the generation of unburnt gas are minimized through an understanding of the distribution of the air-fuel mixture and parts not contributing to combustion based on CFD analysis. Conventionally, by upgrading the shape of the cylinder head or reducing the dead volume areas around the intake and exhaust valves, the amount of unburnt gas (Total Hydro Carbon: THC) was successfully reduced by approximately 30% in 2012. Optimization utilizing CFD further realized the effective reduction of dead volume areas inside the combustion chamber, achieving a total decrease in THC by about 60% combined with the other improvements described above in 2015. (**Figure 5**)

As explained so far, the KU30GSI-Plus engine focuses on stable combustion while successfully increasing the power generating efficiency up to 49.5% (ISO3046).

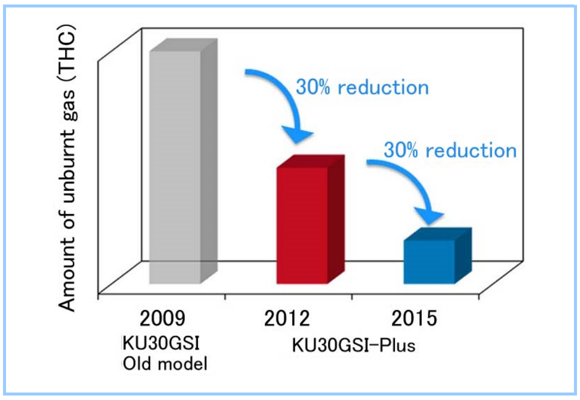

Figure 5 Reduced unburnt gas

4. Technology utilizing energy from gas engine cooling water

The KU30GSI engine achieves a total efficiency of over 80%, taking into account the utilization of steam and warm water, which is widely used in co-generation plants. On the other hand, warm water is not available throughout the year due to some restrictions on the side of consumers. Therefore, we cannot always benefit from the advantages of owning in-house power generation facilities to the maximum extent.

In terms of the utilization of low-temperature waste heat such as warm water, the conventional approaches for converting the heat into some form of usable energy include applications of the Organic Rankin Cycle (ORC) or heat pumps. Under such circumstances, we have come to think that raising the temperature of cooling water in an attempt to improve the efficiency of heat utilization in the auxiliary equipment would be quite significant. For instance, if the temperature of cooling water discharged from the engine could be maintained at 110 to 120°C, low-pressure steam similar to atmospheric pressure could be generated, which would allow us to use a steam compressor in order to back up the steam from the exhaust gas boiler. This would successfully provide valid heat utilization even when warm water is not available.

As shown in **Figure 6**, MHIET commercialized the "The gas engine cogeneration system with all steam recovery," a system, which compresses saturated steam generated by utilizing the cooling water from the KU30GSI engine as a heat source and adds it to the steam generated by exhaust gas boilers and other devices. This system achieved "power generation + steam recovery" efficiency of 71.1% by increasing the amount of steam generated by more than 1.5 times (from about 3.3ton/h to about 5.1ton/h) in the 18KU30GSI engine (50Hz). MHIET began testing a single cylinder engine of this system in 2011. Subsequently, we carried out testing on an actual multiple cylinder unit in 2014 for verification prior to the launch in May 2015.

MHIET developed a new technology for raising the temperature of engine cooling water higher than existing systems through a close examination of combustion and mechanical elements in order to create a new kind of engine applicable to this system.

Generally speaking, when the temperature of cooling water rises, the combustion velocity inside the engine cylinder increases, which requires extra care for the combustion stability. Especially when utilizing fuel gas with a low methane number just like we do in Japan, in order to secure the combustion stability, the power generating efficiency or power output based on the rated capacity would sometimes need to be compromised.

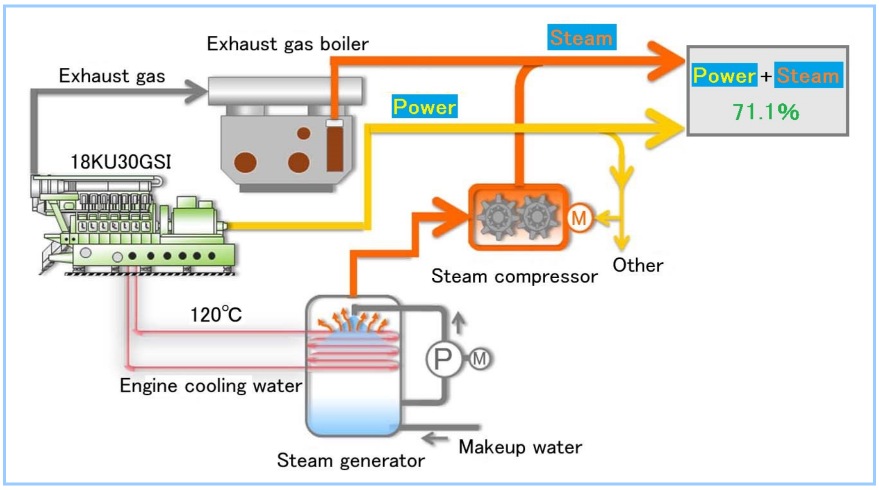

Figure 6 The gas engine cogeneration system with all steam recovery

Figure 7 shows the heat release rate when the temperature of cooling water at the engine outlet is raised from 93 to 120°C. When the water outlet temperature is 120°C, the combustion accelerates and the peak of the heat release rate curve tends to be slightly high. This seems to be due to the accelerated flame propagation caused by the increased wall temperature inside the combustion chamber as mentioned above.

Figure 8 shows the thermal efficiency and COV-Pmax. When we keep the air excess ratio and average peak firing pressure same, as the temperature of cooling water goes up, the thermal efficiency improves, whereas the combustion fluctuation increases, indicating that there is a risk of jeopardizing the combustion stability. In Case C, the thermal efficiency and combustion fluctuation are both optimized, keeping the knocking risk to a minimum.

Although Case C indicates similar efficiency as Case A, we assume that this is due to the reduced cooling loss achieved by the increased temperature of the cooling water and the effects of the reduced amount of unburnt gas realized by some improvements in the combustion efficiency.

Figure 9 shows data indicating the trend of an actual engine unit at the time of startup. According to the trend of the combustion pressure, we can see that, during the rapid startup for about 5 minutes until establishing the rated load, for about 15 minutes until the temperature of cooling water reaches 120°C, and after the temperature settles at 120°C, no abnormal combustion was detected, achieving operation with stable combustion.

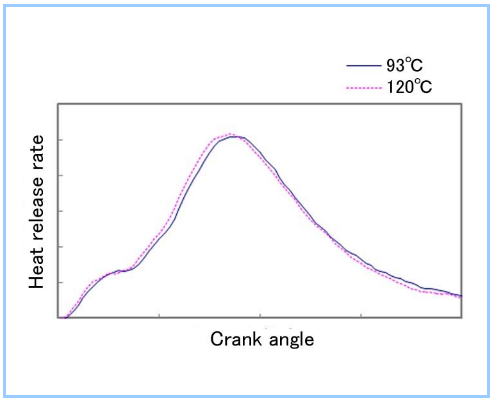

Figure 7 Heat release rate before and after temperature rise of engine outlet cooling water

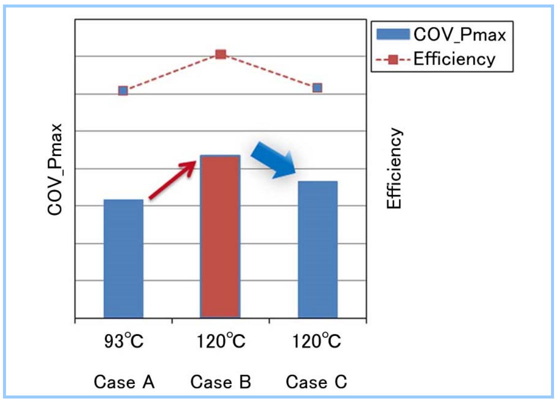

Figure 8 Efficiency and COV Pmax before and after temperature rise of engine outlet cooling water

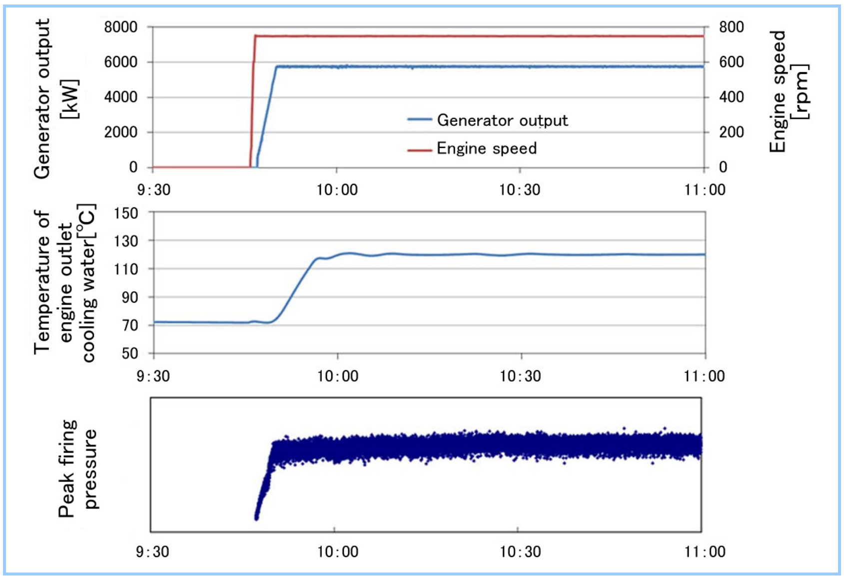

Figure 9 Trend before and after temperature rise of engine outlet cooling water

5. Conclusion

MHIET applied the efficiency-enhancing technology described in this paper to the KU30GSI-Plus engine and achieved a power generating efficiency of 49.5%. Such an improvement in power generating efficiency greatly contributes to the reduction of power generation costs and environmental burden, as well as effective energy use. By adding the KU30GSI/KU30GSI-Plus models to our product lineup, we believe that we will be able to provide the optimum solution not only for heat and power generation applications including CHP, but also for mono-generation which requires high power generation efficiency. The KU30GSI series gas engines offer high startup performance, excellent load following capability and the technology for raising the temperature of cooling water with a high level of flexibility. We strongly believe that we are able to provide the optimum solution for each and every customer need.

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