World's Most Efficient 5MW-Class Gas Turbine, M5A

Under the Paris Agreement, which is a framework aimed at mitigating global warming, promoting cogeneration (combined heat and power application) is increasingly important for realizing a low-carbon society. In particular, gas turbine cogeneration, which enables the utilization of high-temperature steam, is expected to further boost efficiency.

By combining state-of–the-art technologies with Kawasaki's expertise in gas turbines and extensive experience in this field, all the elements are optimized through flow analysis and measured and evaluated the vibration of all the rotor blades in a contactless fashion. M5A was also successfully developed, which is a cogeneration gas turbine with the world's highest efficiency in the 5MW class and reduced NOx emissions. M5A has been adopted in 15 domestic and overseas sites, and the total operation time has exceeded 160,000 hours.

Introduction

Under the Paris Agreement, which is a framework aimed at mitigating global warming, cogeneration is increasingly implemented to realize a low-carbon society because its value as a distributed energy system is appreciated in terms of not only energy savings and CO_2 emissions reductions but also stable electricity supply. In addition, the market has become active as a result of institutional reforms such as liberalization of the electricity and gas retail markets as well as profitability improvement through the development of new technologies. In particular, gas turbine cogeneration, which enables the utilization of high-temperature steam, has been widely implemented mainly in industrial areas, and further efficiency improvement of gas turbines is expected.

1 Background

Since the 1983 market launch of our 1MW-class cogeneration system that employed our proprietary gas turbine, we have built a lineup that includes 30MW-class models to satisfy various market demands. We developed the GPB50D cogeneration system, which is mainly composed of our 5MW-class M5A gas turbine and main unit. The M5A gas turbine realizes best-in-class efficiency and environmental performance by combining the industrial gas turbine development technologies we have accumulated over the years with state-of-the-art technologies while ensuring reliability based on our deep experience and track record [1)].

2 Development concept

We developed the M5A gas turbine as a new model that fills the gap in our lineup between the compact M1A and the medium-sized M7A in order to provide an excellent system to satisfy diversifying demands. **Fig. 1** is a bird's eye view, while **Table 1** lists the main specifications. The features are described below.

(1) Remarkable cogeneration performance

The thermal efficiency of this gas turbine is peerless among 5MW-class gas turbines, exceeding even the trend set by the latest high efficiency models. At the same time, the exhaust gas is set to a suitable temperature for exhaust heat recovery to achieve high overall efficiency.

To ensure the durability of hot sections, the turbine inlet is set to a moderate temperature. The amount of cooling air is reduced to decrease power loss. In addition, we have eliminated issues stemming from its small size and realized both a large operating range and high efficiency; we achieved this by, for example, applying optimization design technology using state-of–the-art flow

† A gas turbine for which we have realized best-in-class power generation efficiency and environmental performance by combining technologies for industrial small- and medium-sized gas turbines accumulated over the years and by applying state-of–the-art technologies, all the while maintaining reliability based on our deep experiences and track record

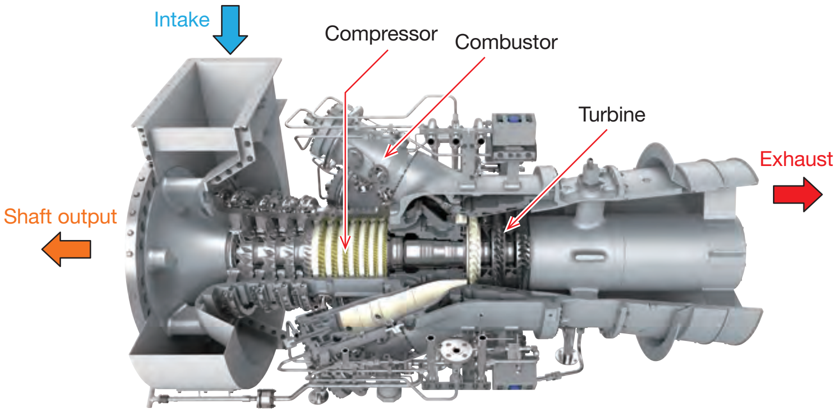


Fig. 1 Bird's eye view of M5A gas turbine

Table 1 Main specifications of M5A gas turbine

Type	Simple open cycle, single shaft
Compressor	Axial 11 stages
Turbine	Axial 3 stages
Combustor	6 cans
Dimensions [m]	L2. 6×H1. 5×W1. 4
Electric output [MW]	4. 96
Thermal efficiency (LHV standard) [%]	33. 0
Exhaust mass flow [kg/s]	17. 6
Exhaust temperature [°C]	523
Emissions	NOx : 52. 5ppm or less (O_2=0%)

※ ISO conditions, no inlet/exhaust pressure loss, 100% CH_4

analysis to every aerodynamic element and adopting a bowed blade as the stator vane at the compressor rear stage.

(2) Best-in-class environmental performance (low NOx)

This gas turbine is equipped with our proprietary pilot, main, and supplemental fuel nozzles. It includes a six-can dry low emission combustor (hereafter referred to as a DLE combustor) that employs the time-proven lean premix combustion method. The gas turbine controls the fuel flow to each fuel nozzle according to the operating status in order to maintain the optimal combustion state and to achieve the highest level of environmental performance (low NOx) in the 5MW class across a wide operating range.

(3) Continuing the reliability of the M1A and M7A gas turbines

During development design, we made it a top priority to ensure the same level of reliability as the time-proven M1A and M7A gas turbines. We also resolved to realize performance and other features at high levels. To do so, we used a proven structure and materials with established quality to achieve overall optimization of characteristics such as functionality, weight, size, maintainability, and operability.

(4) Light weight and compact

We significantly reduced the size while constraining pressure loss by adopting a simple ring casing structure from the M1A gas turbine and applying optimization design based on the most advanced flow analysis to the intake and exhaust flow paths. This resulted in a smaller generator enclosure.

(5) Long maintenance and inspection cycle

To ensure continuous operation, gas turbine maintenance includes an annual bore scope inspection and a quadrennial overhaul. For the overhaul, the existing gas turbine is exchanged with a refurbished one to reduce the maintenance downtime.

(6) Outstanding operability

It just takes 10 minutes for the gas turbine only to start and reach rated output, excluding the time for pre-purging. In addition, the gas turbine supports DLE operation in which it operates with low emissions even during island-operation while delinked from the grid system. This enables the system to tolerate a maximum load rate of 50% even if the load suddenly changes during island-operation, thus realizing outstanding operability.

(7) Performance improvement by leveraging a higher temperature tolerance

Our verification test for long-term reliability using multiple commercial M5A gas turbines confirmed that the hot parts can tolerate higher temperatures. This enabled us to make improvements by raising the operating temperature to harness the potential for performance improvement without making significant design changes.

3 Development program

Aiming for rapid development and a seamless market launch with ambitious development goals, we started a development project in April 2014. We carried out product planning, gas turbine design, and production preparations simultaneously. We started an operation test of the gas turbine in December 2016; completed the series of necessary verifications, including performance and integrity assessment and an endurance test, through an internal operation test that lasted slightly under a year; and completed initial development in October 2017. Then, after conducting a preliminary test to support higher temperatures and assessing the additional overhaul inspection results of commercial M5A gas turbines and other factors, we started a performance improvement project in 2019, which took two years to complete.

After verifying performance and integrity during a development test, we operated the gas turbines under various harsh conditions during an endurance test; we then conducted an inspection and check. When improvement design was necessary, we returned to an upstream process and conducted the tests and assessment again. By preparing for the possibility of this rework in advance and breaking down measurement into detailed measurement and durability/performance measurement using two prototype gas turbines to conduct tests efficiently, we succeeded in completing the tests rapidly.

To check reliability, we used all our expertise that we accumulated through the development of the L30A gas turbine, such as a non-contact blade vibration measurement technology for rotor blades at all stages of the compressor and turbine and a blade surface temperature measurement technology using a pyrometer for rotor blades at all stages of the turbine, for the tests and assessments. We conducted real-time processing and analysis for timely assessment and evaluation, acquiring data on operation test equipment and measuring over 1,000 items in a monitoring system. Typical measurement examples are described below.

(1) Compressor

It is essential to assess the high cycle fatigue of blades because they undergo aerodynamic excitation due to causes such as the wake generated by the front vane. Therefore, we conducted optical non-contact blade vibration measurement for all rotor blades. We captured changes due to blade vibration when the blades passed through a sensor, assessed the vibration, and confirmed integrity through an endurance test. In addition, we are working to apply measurement probes made using additive manufacturing.

(2) Combustor

We assessed amplitude and frequency by measuring pressure fluctuations using a semi-conductor pressure transducer to check combustion oscillation during lean premix combustion. In addition, we used thermocouples and thermal paint together to confirm that the temperature allows for parts durability to be maintained.

(3) Turbine

We applied a pyrometer with superior temperature resolution [2)] to assess the temperature of turbine rotor blades (**Fig. 2**). At the same time, we verified the accuracy assessment that employs thermocouples using a slipring. We also measured the vibration of rotor blades using a gauge during this measurement to assess high cycle fatigue together with separately conducted non-contact blade vibration measurement at the blade tip gaps.

(4) Structure

For the intake and exhaust flow paths designed to be smaller than those of conventional models, we measured the static pressure on the wall surface of each section and the total pressure; we conducted the flow analysis shown in **Fig. 3** for assessment, and confirmed that the paths provide the expected performance.

Despite the short development period, we enhanced product reliability by conducting thorough quantitative assessment as illustrated above during an actual turbine operation test. Meanwhile, we quantitatively recognized the product’s potential for better merchantability and room for further performance improvements.

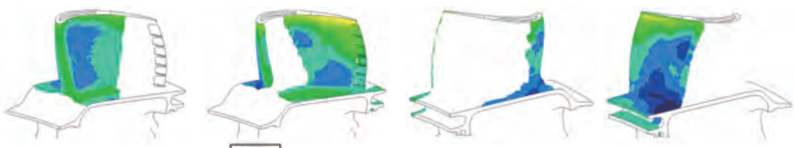


Fig. 2 Results of temperature measurement of turbine rotor blades with pyrometer

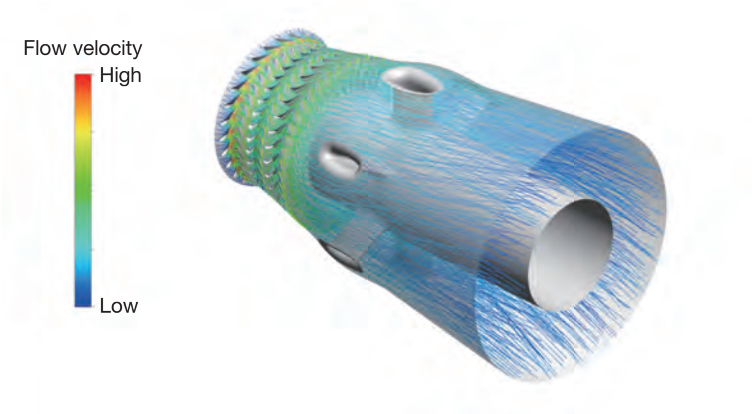


Fig.3 Example of flow analysis of exhaust flow path

4 GPB50D Cogeneration system

Table 2 describes the performance of the GPB50D Kawasaki gas turbine cogeneration system, which employs the M5A gas turbine as its core component in combination with an heat recovery steam generator and other components. The thermal efficiency is higher than that of gas turbines in the same class by about 3 points (32.3%), and the total efficiency is higher by about 3 points (85.3%), thus providing high economic efficiency. The NOx value of this system offers best-in-class environmental performance.

As a typical example, the GPB50D for domestic can reduce energy consumption by 20.9% and CO_2 emissions by 17.5% compared to conventional systems, which use commercial electricity and a gas boiler. Moreover, energy costs are expected to be reduced by about 350 million yen a year compared to conventional systems under conditions such as a purchased electricity cost of 20 yen/kWh and a city gas cost of 100 yen/m^3N.

Table 2 Cogeneration performance of GPB50D

Model	［GPB50D］
Gas turbine model	［M5A-01D］
Electric output [kW]	4, 685
Fuel consumption [Nm^3/h]	1, 287
Steam mass flow [kg/h]	10, 980
Thermal efficiency [%]	32. 3
Heat recovery efficiency [%]	53. 0
Total efficiency [%]	85. 3
NOx value（O_2 = 0%）（DLE operating range）[ppm]	52. 5（50% to 100% load）

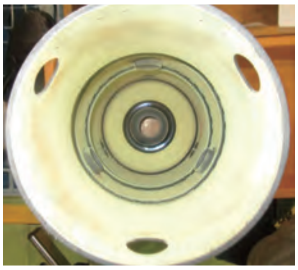
Intake temperature: 15°C, atmospheric pressure: 101. 3 kPa（at an altitude of 0 m）
Intake/exhaust pressure loss: 0. 98/2. 94 kPa
Fuel: City gas 13A
Heat recovery steam generator: Steam pressure of 0. 78 MPaG, supply water temperature of 60°C

5 Operation experience

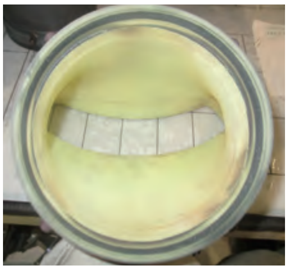
The first model delivered to a domestic user started commercial operation in July 2018. In this project, we upgraded an existing gas turbine cogeneration system having lower economic efficiency and environmental performance with a new model. We reused the existing system to the extent possible, including the foundation, accessories, stack, and electrical equipment.

After about three years had elapsed since the start of operation, we conducted an additional overhaul inspection of the gas turbine. The gas turbine was brought back from the site, completely disassembled it at our factory, and conducted a visual inspection, dimensional inspection, and non-destructive inspection. To assess long-term durability, we reassembled the gas turbine without replacing any parts except for some samples taken during the destructive inspection, and returned it to the customer's site for continued operation.

Fig. 4 shows photographs of combustor parts and turbine rotor blades during a factory inspection. All parts were in very good condition, and no harmful defects were found. We confirmed rubbing was not excessive but rather moderate at the blade tips and the clearance of the labyrinth seal section, and we demonstrated that three-year operation poses no issues in terms of durability and



(a) Combustor chamber



(b) Transition duct

(c) 1st-stage rotor blade

(d) 2nd-stage rotor blade

(e) 3rd-stage rotor blade

Fig.4 Example of hot gas path parts at additional overhaul inspection at factory

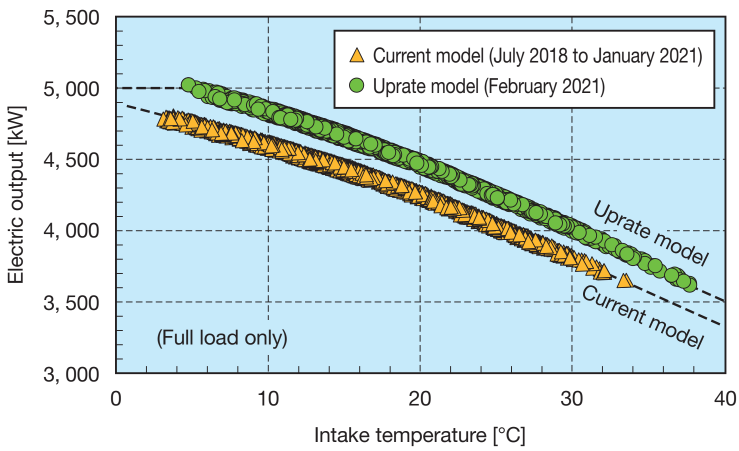


Fig. 5 Trends in performance after application of M5A gas turbine with uprate performance

stability.

After this additional overhaul inspection, the user introduced the M5A gas turbine with uprate performance. The gas turbine has achieved the planned performance as shown in **Fig. 5**, and features such as fuel consumption and steam amount did not deteriorate during operation. Going forward, we will accumulate actual operation cases, continue to observe progress through planned inspections, and demonstrate reliability by assessing long-term durability and stability.

Conclusion

We expect that the M5A gas turbine with outstanding features such as worldwide best-in-class efficiency and environmental performance will drive cogeneration implementation in light of policy support for CO_2 emissions reduction and rising awareness regarding business continuity through energy supply in emergencies. We will also continue to further improve merchantability to contribute to solving energy and environmental issues around the world.

References

1) S. Ishihara, et al., "DEVELOPMENT OF HIGH EFFICIENCY 5 MW CLASS GAS TURBINE THE KAWASAKI M5A," ASME Paper GT2019-90773.
2) T. Horiuchi, et al., "APPLICATION OF CONJUGATE HEAT TRANSFER ANALYSIS TO IMPROVEMENT OF COOLED TURBINE VANE AND BLADE FOR INDUSTRIAL GAS TURBINE," ASME Paper GT2018-75669.

P.E.Jp (Mechanical Engineering)
Takuya Ikeguchi
Planning Department, Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Hiroshi Kubo
Gas Turbine Development Department,
Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Shinya Ishihara
Gas Turbine Development Department,
Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Motoki Yoshimura
Gas Turbine Development Department,
Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Keishiro Takeda
Gas Turbine Development Department,
Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Tomoki Taniguchi
Gas Turbine Development Department,
Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Toshiaki Sakurazawa
Gas Turbine Engineering Department,
Energy System Group,
Energy Solution Business Division,
Energy Solution & Marine Engineering Company

Yuuki Ishitobi
Mechanical System Research Department,
Technical Institute,
Corporate Technology Division

Takeshi Horiuchi
Climate Change Projects Office,
Climate Change Policy Division,
Global Environment Bureau,
Ministry of the Environment *

*as of the writing of this article:
Energy System Research Department,
Technical Institute,
Corporate Technology Division