Development of 1650℃ Class Next Generation JAC Gas Turbine based on J Experience

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Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has continued to contribute to the preservation of the global environment and the stable supply of energy through constant gas turbine development based on our abundant operating results, research and verification of state-of-the-art technology. In recent years, using results from the "1700°C Class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project that we have participated in since 2004, MHPS has developed the highly-efficient M501J, which achieved the world's first turbine inlet temperature of 1600°C, and has accumulated operating results around the world. This report presents the development status of the next-generation 1650°C class JAC (J Air Cooled) gas turbine, which is based on the proven J-series and uses an enhanced air-cooled system for cooling the combustor, ultra-thick TBC (thermal barrier coating) and a compressor with a high pressure ratio as core technologies. These have been verified as individual components, and actual equipment verification using the verification facility in the MHPS Takasago Works is planned to commence in 2020 for final verification.

1. Introduction

In recent years, in terms of the preservation of the global environment and the stable supply of energy, the importance of gas turbine combined cycle power plants (GTCC), which have higher efficiency and operability than conventional thermal power plants, has been increasing. For higher GTCC efficiency, a higher temperature of the gas turbine has played an important role, and MHPS developed the M701D, a 1150°C class, large-capacity gas turbine, in the 1980s. This was followed by the M501F, which had a turbine inlet temperature of 1350°C, and the M501G, which employs a steam-cooled combustor and has a turbine inlet temperature of 1500°C (**Figure 1**). Through these developments, we have demonstrated high plant thermal efficiency and reliability, as well as low emission. From 2004, we participated in the national project "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" to take on research and development of the latest technology necessary for higher temperature/efficiency and used the results of the development to develop the M501J, which achieved the world's first turbine inlet temperature of 1600°C. Verification operation of the M501J GTCC started in 2011 at the demonstrator (T-point) in the MHPS Takasago Works and operating results have steadily accumulated.

The J-series gas turbine adopts the steam-cooled system for cooling the combustor, but if an air-cooled system can be used while maintaining the high turbine inlet temperature, further

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improvement in the efficiency and operability of GTCC can be expected. Therefore, MHPS worked on the development of next-generation GTCC that realizes air cooling of high-temperature gas turbines, and devised the enhanced air-cooled system that is a core technology thereof. In the spring of 2015 we completed the verification test of the entire system at T-point in the MHPS Takasago Works, and since then we have been performing long-term operation for more than 10,000 hours. This report presents the development and operational status of MHPS's state-of-the-art, high-efficiency gas turbine and the development of the next-generation 1650°C class JAC gas turbine using an enhanced air-cooled system for cooling the combustor, ultra-thick TBC (thermal barrier coating) and a compressor with a high pressure ratio as core technologies.

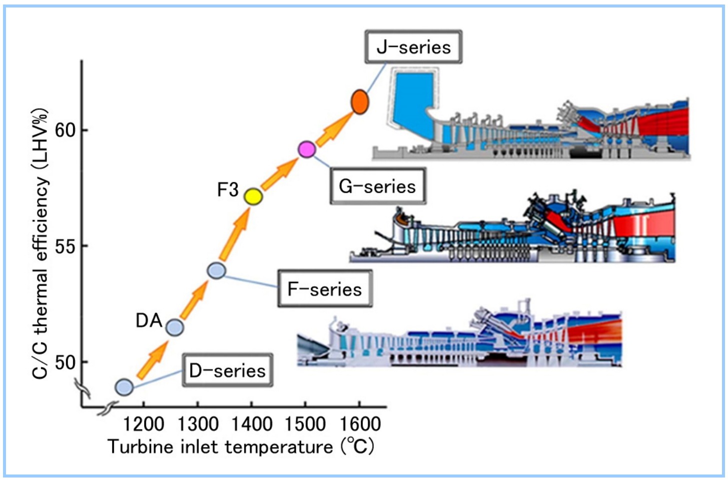


Figure 1 History of development of large gas turbine models

2. Development and results of M501J gas turbine

The M501J can achieve a turbine inlet temperature of 1600°C based on the component technologies already demonstrated by the abundantly-proven F-series gas turbine and G-/H-series gas turbines, with turbine inlet temperature classes of 1400°C and 1500°C, respectively, and the application of the development of the most advanced 1700°C class technology resulting from the national project. As a result of the increase of the turbine inlet temperature and the adoption of the latest component technology, the GTCC power generation end thermal efficiency has greatly increased in comparison with existing equipment. CO_2 emissions can be reduced by about 60% when a conventional coal-fired thermal power plant is replaced with a natural gas-fired J-series gas turbine combined cycle power plant. **Figure 2** lists the technical features of the M501J.

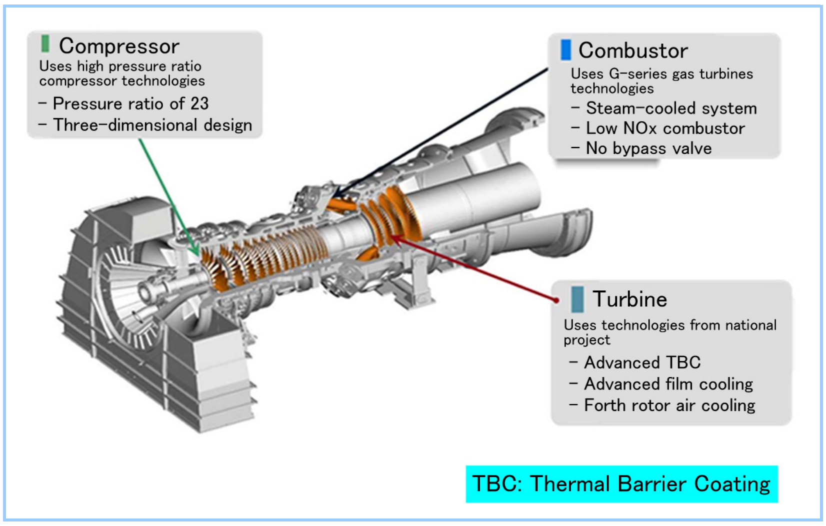


Figure 2 Technological characteristics of M501J gas turbine

The development of the M501J gas turbine was carried out by conducting verification tests of each component at the basic design stage, reflecting the results in the detailed design, and finally verifying the actual operation of the entire gas turbine in the demonstration power generation facility. **Figure 3** depicts the appearance of the gas turbine combined cycle power plant demonstrator (known as T-point) in the MHPS Takasago Works. We carried out 2,300 special measurements on the first model of the M501J and verified that the performance, mechanical characteristics and combustion characteristics satisfied the target values before the shipping of the commercial product. We have received orders for 57 J-series gas turbines from domestic and overseas customers, and are shipping them as they become available. Up to now, 39 units have been put into commercial operation, and the total operational time of more than 768,000 hours has been reached. (**Figure 4**)

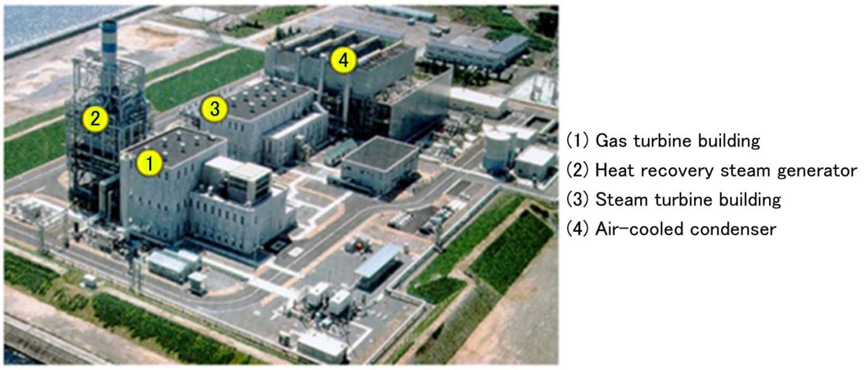


Figure 3 Gas turbine combined cycle power generation plant demonstrator (T-point) in the MHPS Takasago Works

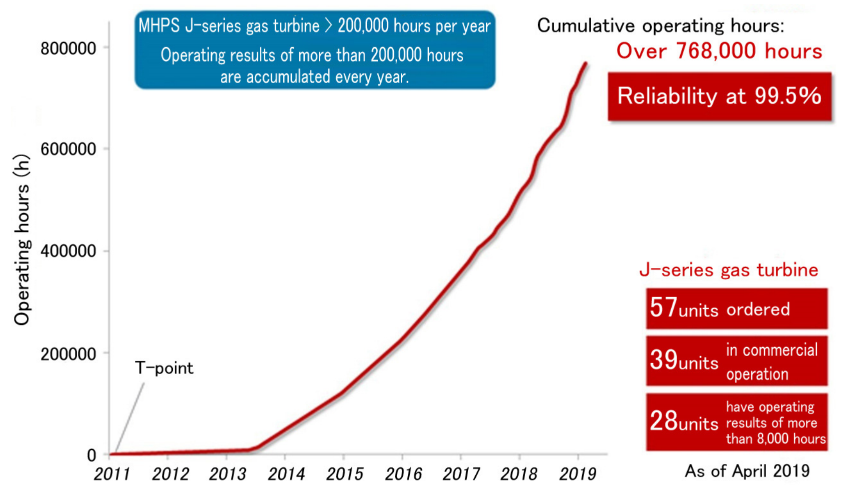


Figure 4 Operating results of M501J gas turbine (including 50 Hz units)

3. Basic concept of next-generation 1650°C class JAC gas turbine

MHPS has been proceeding with the development of the next-generation 1650°C class JAC gas turbine with improved efficiency and operability compared with the J-series by applying to the proven J-series the following verified component technologies: (1) an enhanced air-cooled system for cooling the combustor, (2) ultra-thick TBC (thermal barrier coating) and (3) a compressor with a high pressure ratio. (**Figure 5**)

The basic concept of this gas turbine includes the following:

(1) Adopting an enhanced air-cooled system to improve operability and increase the turbine inlet temperature.

(2) Adopting ultra-thick TBC developed based on the technology resulting from the national project to achieve both high performance and reliability despite the turbine inlet temperature of +50°C compared with that of 501J.

(3) Adopting a compressor with a high pressure ratio design equivalent to the H-series to suppress the increase of the exhaust gas temperature at the gas turbine outlet.

As shown in **Figure 6**, the above component technologies have been verified individually, and reflected in and applied to the JAC gas turbine.

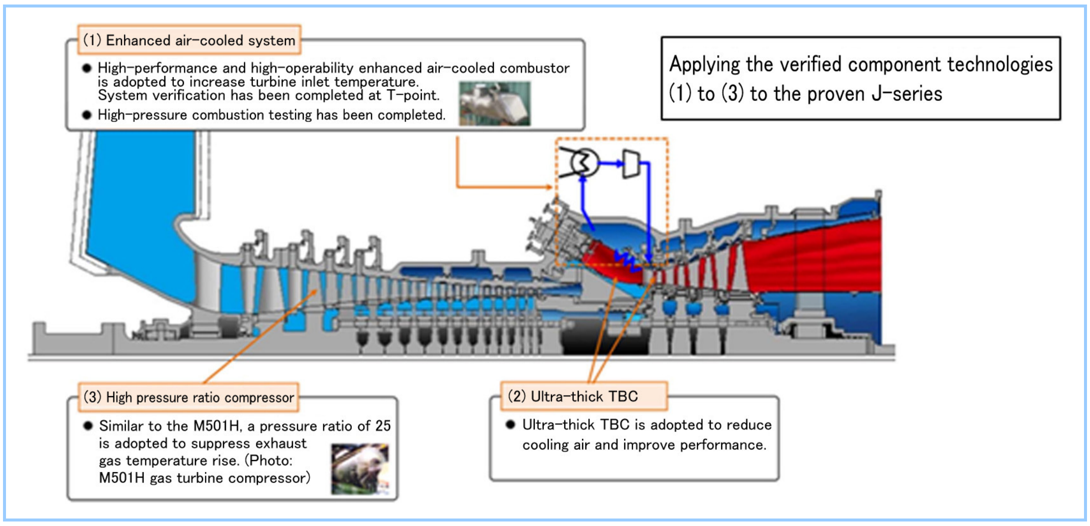


Figure 5　Basic concept of next-generation 1650°C class JAC gas turbine

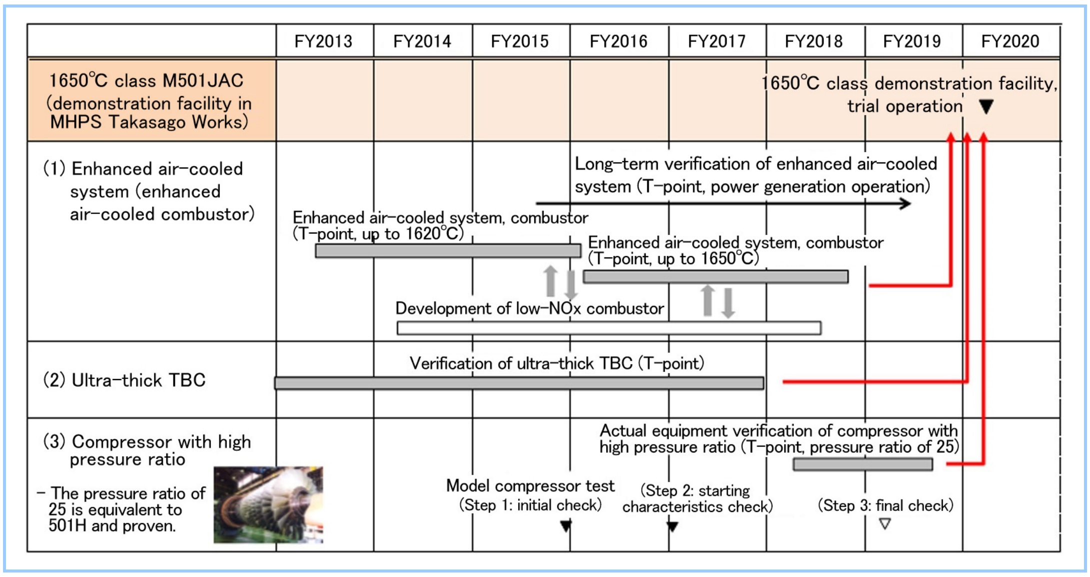


Figure 6　Roadmap for application of component technology to 1650°C class JAC gas turbine

Table 1 compares the performance of the J-series and JAC-series gas turbines.

Table 1　Gas turbine performance (ISO, standard conditions)

	M501J	M501JAC
Frequency (Hz)	60	60
Pressure ratio	23	25
Gas turbine output (MW)	330	425
Gas turbine efficiency (%-LHV)	42	44
Combined cycle output (MW)	484	614
Combined cycle efficiency (%-LHV)	62	64

4. Verification status of component technologies used for next-generation 1650°C class JAC gas turbine

This section describes the verification status of the component technologies used for the JAC gas turbine. As detailed in Figure 6, these component technologies have been verified as individual components, and actual equipment verification is planned to be performed from 2020 for final verification.

4.1　Enhanced air-cooled system for cooling combustor

The J-series gas turbine adopts the steam-cooled system for cooling the combustor, but if an air-cooled system can be used while maintaining the high turbine inlet temperature, further improvement in the efficiency and operability of GTCC can be expected. Therefore, MHPS devised an enhanced air-cooled system that is a technology for realizing air cooling of high-temperature gas turbines. By adopting this enhanced air-cooled system, air cooling of gas turbines even with a turbine inlet temperature of 1650°C can be realized, enabling an increase in combined power generation efficiency and the operability of the entire plant. In the spring of 2015, we completed the actual equipment verification test of the entire system at T-point. An overview of the air-cooled system is presented below.

In the enhanced air-cooled system, air extracted from the compressor outlet (combustor casing) is cooled by the enhanced cooling air cooler, pressurized by the enhanced cooling air compressor, used for cooling the combustor and then returned to the casing. **Figure 7** presents a schematic diagram of the enhanced air-cooled system.

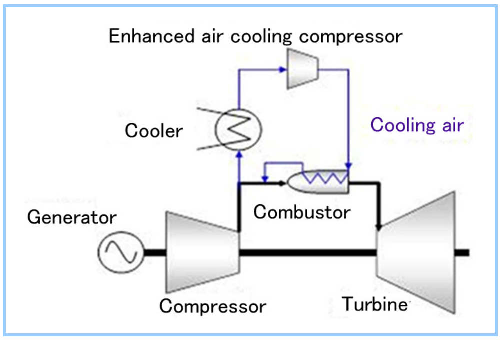


Figure 7 Schematic diagram of enhanced air-cooled system

The characteristics of the enhanced air-cooled system are described below.

(1) The efficiency of the system can be improved by recovering the waste heat of the enhanced cooling air cooler on the bottoming cycle side.
(2) Cooling performance equal to or higher than that of the existing steam-cooled system can be achieved by optimizing the combustor cooling structure.
(3) The startup time of the entire GTCC can be shortened in comparison with the steam-cooled system.

It is important for improving the efficiency of next-generation GTCC with an enhanced air-cooled system to develop a combustor that can be efficiently cooled with a small amount of cooling air, reduce the waste heat from the enhanced cooling air cooler, improve the recovery efficiency and reduce the power of the enhanced cooling air compressor.

<u>Enhanced air-cooled system actual equipment verification</u>

Figure 8 provides an overview of the facility and a system overview of the enhanced air-cooled system verification executed at T-point.

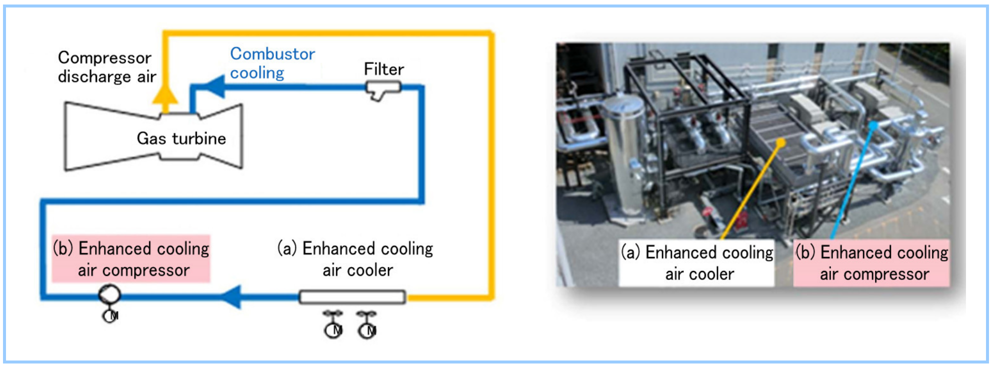


Figure 8 Enhanced air-cooled system verification equipment and system of T-point

In the spring of 2015, we verified the operability of the enhanced air-cooled system, that is, the responsiveness to transient changes such as start/stop, load change and load rejection, using the T-point demonstrator, and confirmed that there was no problem. The enhanced cooling air compressor operating point behavior during a gas turbine trip test was also tested and it was confirmed that the enhanced cooling air compressor could be stopped safely without entering a surging state at a trip from 100% load of the gas turbine.

Long-term operational verification of the enhanced air-cooled system is still being performed at T-point, and the operating result of more than 10,000 hours has been accumulated.

Based on this enhanced air-cooled system, we also verified a system that enables clearance control during load operation. This system includes two supply systems. One supply method supplies cooling air to the combustor directly by bypassing the turbine blade ring, and the other method supplies cooling air to the combustor after ventilating the turbine blade ring to maximize performance by reducing the turbine clearance during load operation. These two systems can be switched using the switching valve (three-way valve) even during load operation. The former system makes it possible to cope with a large load changing operation by opening the clearance (Flexible Mode). On the other hand, the latter makes it possible to reduce the clearance during load operation and maximize performance (Performance Mode). **Figure 9** illustrates the clearance behavior when the three-way valve is switched during load operation. Using this system, it is expected that operability can be further improved while maximizing performance.

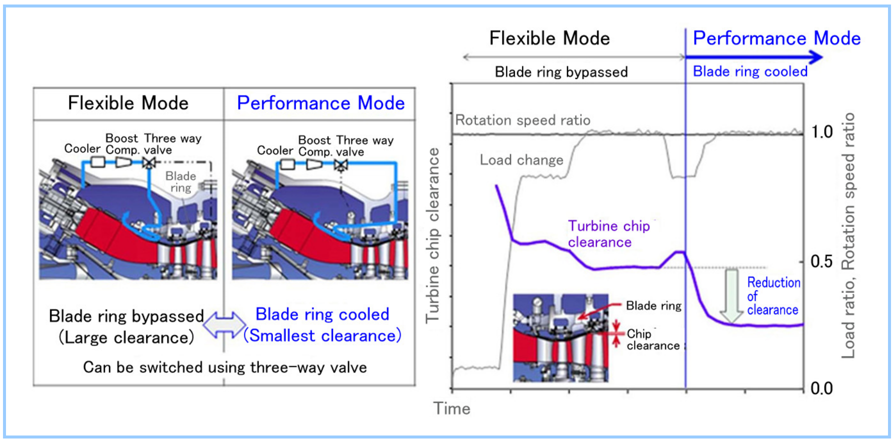


Figure 9 Turbine clearance control using enhanced air-cooled system

4.2 Ultra-thick TBC (Thermal Barrier Coating)

Although the turbine inlet temperature of the 1650°C class JAC gas turbine can become 50°C higher than that of the M501J, ultra-thick TBC is adopted to achieve both high performance and reliability. Generally, the durability decreases as the TBC is thickened, but the TBC developed based on the technology resulting from the national project has higher durability, making ultra-thick TBC possible. Prior to application to the actual blade, for application verification of ultra-thick TBC, coupon test pieces were sampled to check the microstructures and porosity, and then thermal-cycle-tested to confirm that there were no problems in terms of durability. In the actual equipment verification, ultra-thick TBC was applied to the combustor, the first to third stage turbine rotors and stator blades, as well as the ring segments, and the reliability was confirmed through long-term verification. **Figure 10** shows the verification status of ultra-thick TBC on the first stage turbine stator blade.

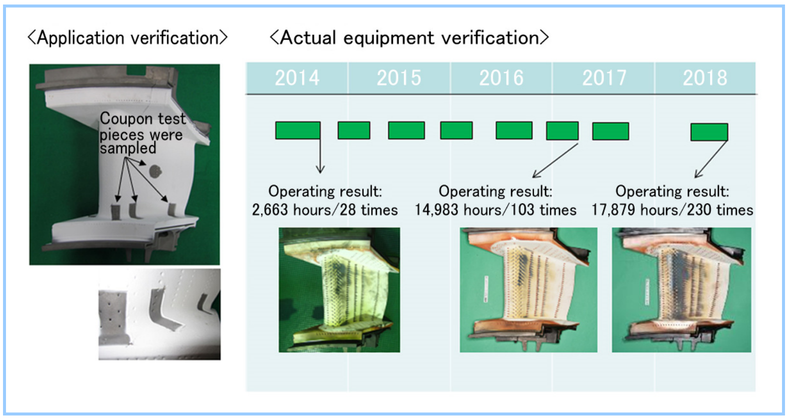
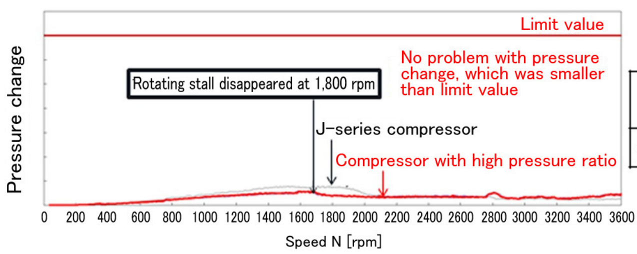


Figure 10 Verification status of ultra-thick TBC on first stage turbine stator blade

4.3 Compressor with high pressure ratio

The compressor of the 1650°C class JAC gas turbine has a high pressure ratio design equivalent to our H-series, which has operating results, and suppresses the increase of the exhaust gas temperature due to the increase of the gas turbine inlet temperature by increasing the pressure ratio from 23 adopted by the J-series to 25. Since a high pressure ratio compressor is designed to have a relatively reduced outlet flow area, there is concern that the flow rate will decrease during startup when the pressure ratio is low and result in a relatively heavy rotating stall. However, MHPS has performed verification with an H-series compressor (with a pressure ratio of 25) at T-point in 2001. We also performed actual equipment verification of the compressor that was designed based on the J-series and had a pressure ratio of 25 at T-point in May 2018. As a result, it was confirmed that the starting characteristics and aerodynamic performance were good. (**Figure 11**)



	501J-series	Compressor with high pressure ratio based on J-series
Pressure ratio	23	25

Figure 11 T-point verification results of starting characteristics of compressor with high pressure ratio based on J-series

4.4 Additive manufacturing of high-temperature parts

With the aim of improving performance by reducing the cooling air for gas turbine high-temperature parts (stator blades and ring segments), we are developing a technology for metal additive manufacturing of complex cooling structures that cannot be manufactured using the current method. To ensure the material strength of an additive manufactured object, which was one of the issues we faced, we worked on the adjustment of the material composition and optimization of the manufacturing and heat treatment processes and obtained the required strength of metal additive manufactured objects in high-temperature environments. At present, a verification test is being conducted on a gas turbine high temperature part (first stage ring segment). Moving forward, we plan to work on the development of a technology for high-precision manufacturing of complex structures in the future.

Figure 12 Demonstration test piece of metal additive manufactured split ring

5. Actual equipment verification of next-generation 1650°C class JAC gas turbine

The 1650°C class JAC is a gas turbine that is based on the proven J-series and uses verified component technologies. These individual components have been verified, and the actual equipment verification of the first model is planned to be performed from 2020 for final verification. This section describes the manufacturing status of the gas turbine first model and the renewal status of the demonstrator in Takasago Works.

5.1 Manufacturing status of first engine of next-generation 1650°C class JAC gas turbine

The compressor, combustor and turbine blade of the 1650°C class JAC gas turbine were designed based on the gas turbine design basic concept described in section 3 and the component development verification results described in chapter 4, and the first engine was manufactured. High-speed rotation tests of the rotating parts were conducted in December 2018. Through the vibration tests of the rotor shaft, compressor rotor blades and turbine rotor blades, it was confirmed that there were no problems of detuning (**Figure 13**). Based on this result, we shipped the main body to the demonstration test facility in June 2019. (**Figure 14**, **Figure 15**)

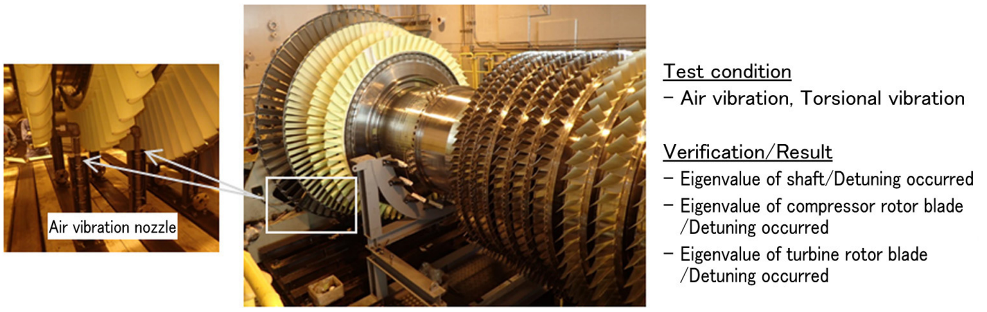


Figure 13　High-speed rotation test of M501JAC gas turbine

Figure 14　Final installation of rotor for M501JAC

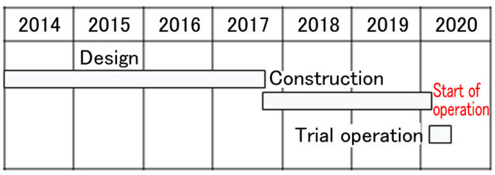
Figure 15　Shipping of M501JAC gas turbine main body

5.2　Renewal status of GTCC verification plant

It is necessary for conducting verification test operation of a newly-developed GTCC to renew not only the main body of the gas turbine, but also the main equipment such as the existing generator, main transformer, heat recovery steam generator, etc., to meet the specifications of the next-generation gas turbine. Therefore, we closed the existing demonstrator (T-point) and are conducting renewal work to construct a new demonstration facility. **Figure 16** depicts the construction status of the new demonstration facility.

Next-generation gas turbine demonstration facility(Panoramic view of construction site as of June 2019)

	Current state	Future state
Output	389,000 kw	566,000 kw
Fuel	City gas, Diesel fuel	City gas, Diesel fuel
Start of operation	June 1997	2020



Existing demonstrator will be renewed and actual equipment verification of 1650°C class JAC gas turbine is planned

Figure 16　Next-generation JAC series gas turbine demonstration facility

Currently, we are preparing for the start of demonstration of the next-generation 1650°C class JAC in 2020. Similar to past G- and J-series gas turbines, we will steadily move forward with the verification of the newly-developed gas turbine using the new demonstration facility, and respond to social needs for further energy saving and the reduction of pollution.

6. Conclusion

For the improvement of the efficiency of GTCC, increasing the gas turbine temperature plays an important role. MHPS developed the highly-efficient M501J, which achieved the world's first turbine inlet temperature of 1600°C based on the development results from the national project "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development," which we have participated in since 2004, and has been steadily accumulating operating results. To further improve the efficiency and operability of GTCC, MHPS is developing the next-generation 1650°C class JAC gas turbine based on the proven J-series, using an enhanced air-cooled system for cooling the combustor, ultra-thick TBC and a compressor with a high pressure ratio as core technologies. These have been verified as individual component technologies, and actual equipment verification is planned to be conducted for final verification. We closed the existing T-point demonstrator, and verification using a new demonstration facility will commence in 2020.

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