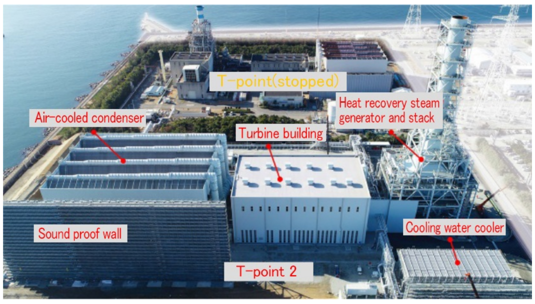
Operation Status of 1650°C Class M501JAC Gas Turbine at T-point 2 Power Plant Demonstration Facility



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Renewable energy has become more widespread in recent years. At the same time, the importance of gas turbine combined cycle (GTCC) power generation has also been on the rise because of the power supply instability of renewable energy. For higher GTCC efficiency, a higher temperature of the gas turbine is important. Mitsubishi Power, Ltd. (Mitsubishi Power) developed the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C, utilizing the development results from the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project in which it has participated since 2004. We have since steadily accumulated operating results. At T-point 2 in January 2020, we started test operation of the next-generation 1650°C class JAC series gas turbine, which is based on the proven J series and uses an enhanced air-cooled system for cooling the combustor, a thicker TBC (thermal barrier coating) and a compressor with a high pressure ratio as its core technologies, all of which have been validated as individual elements at the T-point demonstration facility. The final confirmation of the integrity of equipment reliability, performance, etc., was completed and commercial operation started in July 2020. This report presents the verification results of the test operation and the operation status thereafter.

1. Introduction

Since it has recently become very important to reduce CO2 emissions, power supply by renewable energy sources such as wind power generation and solar photovoltaic power generation has been planned and carried out. However, such renewable energy sources are unstable and natural fluctuations are unavoidable and present concerns such as sudden frequency and load fluctuations in the power system. Against this background, GTCC power generation, which is more efficient and more operable than conventional thermal power generation, is becoming more important in terms of global environmental conservation and a stable energy supply. For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. We 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 employed a steam-cooled combustor and had a turbine inlet temperature of 1500°C (**Figure 1**). Through these developments, we have verified the high plant thermal efficiency and reliability, as well as low emissions. From 2004, we participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project to conduct research and development of the latest technology necessary for higher temperature and efficiency and utilized the results of these

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efforts to develop the M501J, which attained the world's first turbine inlet temperature of 1600°C. Verification operation of the M501J GTCC started in 2011 at the gas turbine combined cycle power plant demonstration facility (T-point) located in Mitsubishi Power Takasago Works and operating results have been steadily accumulated.

The J series gas turbine adopts a 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 is expected. Therefore, we 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 one of its core technologies. In the spring of 2015, we completed the validation test of the entire system at T-point and since then the system has been in operation for more than 10,000 hours. This core technology is applied to the next-generation high-efficiency JAC (J-Air-Cooled) series gas turbine, which has achieved a high turbine inlet temperature of 1650°C. We have been proceeding with the construction of the second gas turbine combined cycle power plant demonstration facility (hereinafter referred to as T-point 2) located in Mitsubishi Power Takasago Works for long-term actual-equipment validation of the JAC series gas turbine. T-point 2, which is state-of-the-art GTCC equipment with an output of 566 MW that combines the 1650°C next-generation JAC high-efficiency gas turbine and the newly-developed high-efficiency steam turbine, has been in test operation since January 2020 and achieved a combined rated output of 566 MW on April 2. We then carried out various tests and adjustments necessary to operate T-point 2 as a power plant, completed all the functional confirmations and started commercial operation on July 1. Due to the adoption of the JAC series gas turbine, the power generation efficiency of the GTCC reached 64%. During test operation, in order to verify the underlying technology, we carried out thousands of temporary large-scale measurements in addition to those provided by regular measurement instruments and monitored and evaluated them online. This report presents the development concept of the state-of-the-art high-efficiency JAC series gas turbine, the verification results obtained at the T-point 2 demonstration facility and the operation status including commercial operation for about one year thereafter.

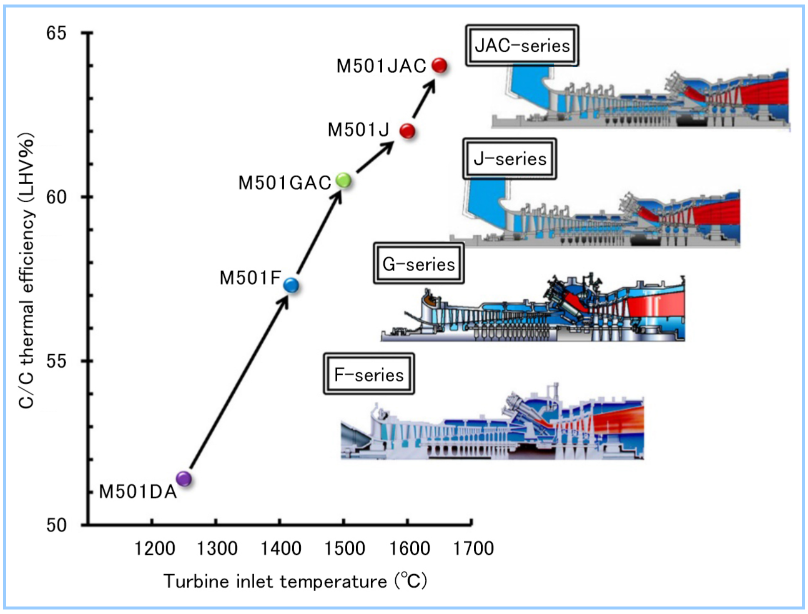

Figure 1 Developmental trend of large gas turbine models

2. Development concept of 1650°C class M501JAC gas turbine

We proceeded with the development of the next-generation 1650°C class JAC series gas turbine in order to further improve the efficiency and operability by applying to the proven M501J gas turbine the following validated component technologies: (1) an enhanced air-cooled system for cooling the combustor, (2) a thicker TBC and (3) a compressor with a high pressure ratio.

The basic concept of this gas turbine is as follows (**Figure 2** and **Figure 3**). Validation of these individual component technologies was completed at the T-point demonstration facility and they were then applied to the 1650°C class JAC series gas turbine (**Table 1**).

(1) Adopting an enhanced air-cooled system to improve operability and increase the turbine inlet temperature in comparison to that of the J series.

(2) Adopting a thicker TBC developed based on the technology resulting from the national project to achieve both high performance and reliability despite the increased turbine inlet temperature.

(3) Adopting a compressor with a high pressure ratio design equivalent to the M501H (validated from 1999 to 2000, hereinafter referred to as the H series) to suppress the increase in the exhaust gas temperature at the gas turbine outlet.

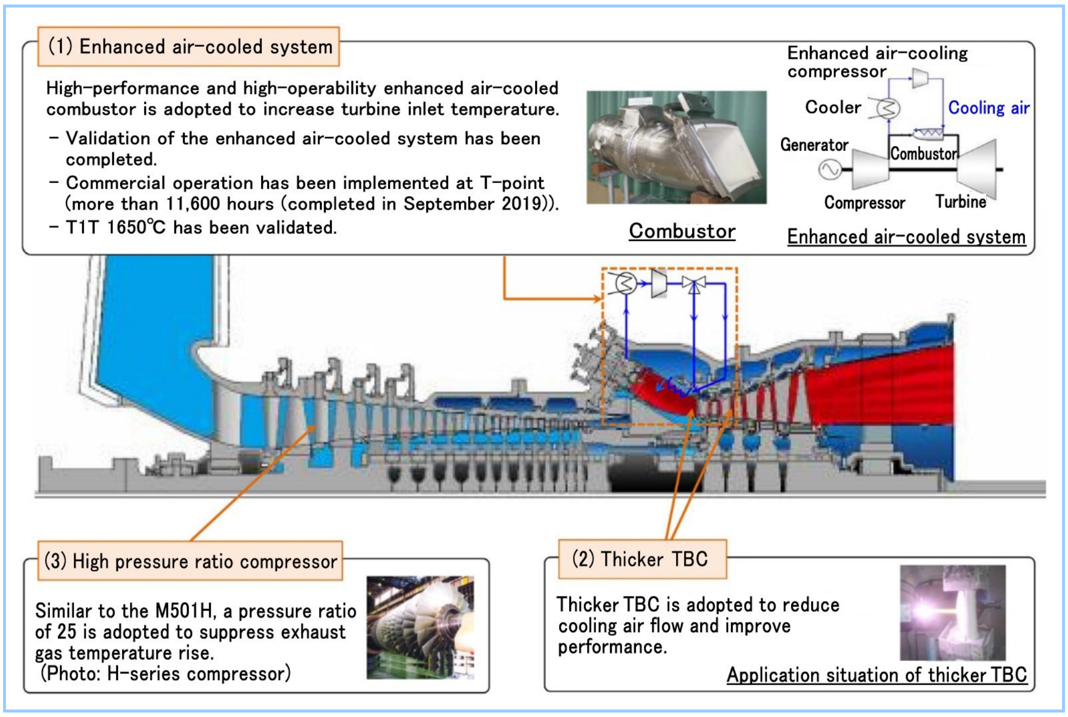

Figure 2 Development concept of 1650°C class JAC gas turbine

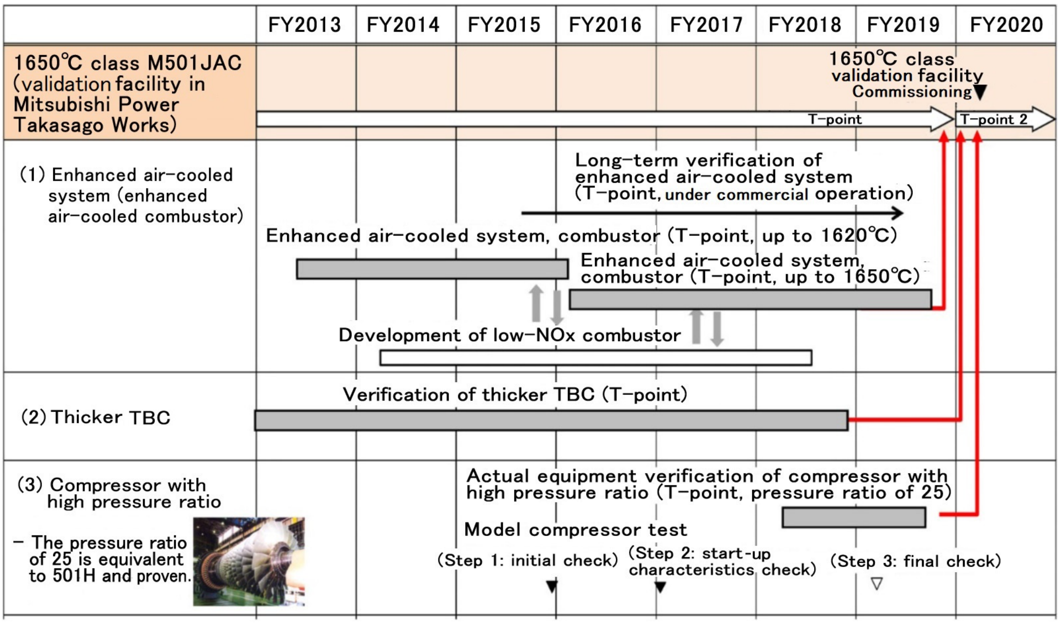

Figure 3 Application flow of component technology to 1650°C class JAC gas turbine

Table 1 Comparison of gas turbine performance (ISO, standard conditions)

	M501J	M501JAC
Frequency (Hz)	60	60
Pressure ratio (-)	23	25
Gas turbine output (MW)	330	435
Gas turbine efficiency (%-LHV)	42	44
Combined cycle output (MW)	484	630
Combined cycle efficiency (%-LHV)	62	>64

3. Verification results and operation status of the 1650°C class M501JAC gas turbine at T-point 2

T-point 2 is a state-of-the-art GTCC facility with an output of 566 MW that combines a 1650°C next-generation high-efficiency JAC series gas turbine and a newly-developed high-efficiency steam turbine. The M501JAC gas turbine was shipped and installed in the spring of 2019 and test operation at T-point 2 commenced in January 2020. In this test operation, first the gas turbine alone was operated and reached its rated load after 10 starts from the first ignition. After steam ventilation, the operability confirmation test was carried out by Combined Cycle (CC) operation and commercial operation began on July 1 (**Figure 4** and **Figure 5**). In test operation, we constantly monitored the start-up acceleration, no-load rated speed and state quantity during partial-load and rated-load operation of the gas turbine in order to make a final confirmation of the reliability, actual performance, exhaust gas emissions, etc., of the equipment. Next, functional tests and special tests required for actual commercial plants were completed.

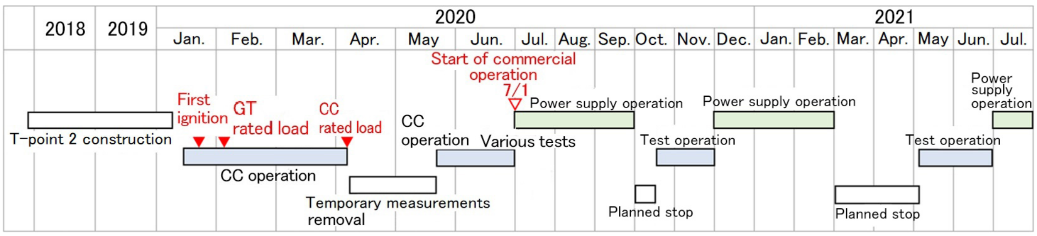

Figure 4 Test operation schedule at T-point 2

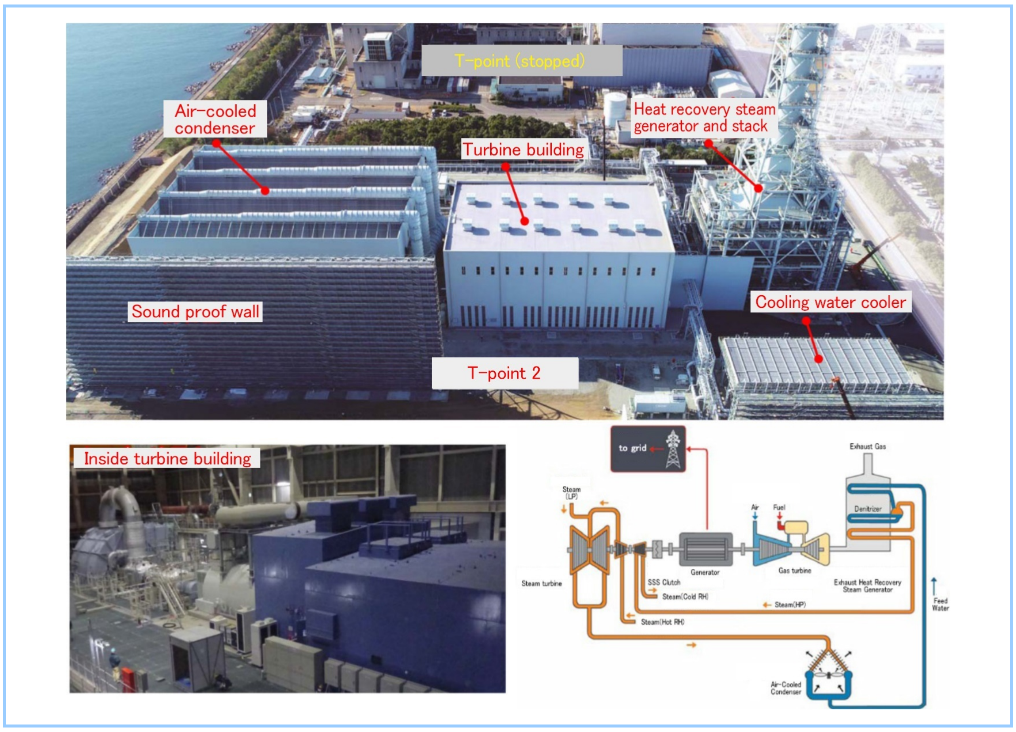

Figure 5 Overview of T-point 2 combined cycle plan

During test operation, more than 2,800 temporary large-scale measurements were conducted to evaluate the integrity in order to verify the technologies that are the basis of the JAC series gas turbine. For the rotating parts, roughly 100 large-scale telemetric measurements were carried out to confirm the metal temperature and vibration stress integrity of the compressor rotors and turbine blades. This chapter presents the final confirmation results of the integrity of each component (**Figure 6**), as well as the status following the commercial operation verification test run over approximately one year after the final integrity confirmation observed in the inspection during a planned stop in March 2021.

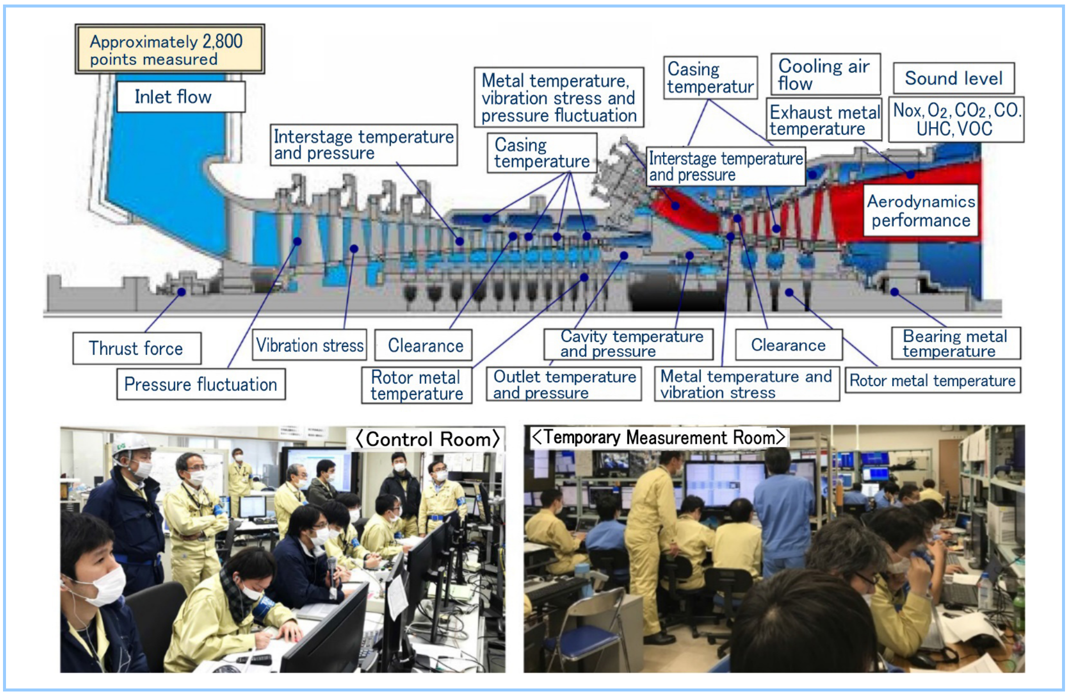

Figure 6　Implementation status of test operation and temporary measurements

3.1 Enhanced air-cooled combustor and enhanced air-cooled system

The enhanced air-cooled system had already been validated at the T-point demonstration facility, including its ability to follow transient changes. In addition, the metal temperature of the enhanced air-cooled combustor was measured in this test operation and its cooling performance in the actual equipment was ultimately validated. As a result, it was confirmed that the combustion casing metal temperature distribution was lower than the design allowance value, so there were no problems in terms of cooling performance (**Figure 7**). It was also confirmed that there were no particular problems with the combustion vibration characteristics and exhaust gas emissions and stable operation was possible under partial-load to rated-load conditions.

The JAC series gas turbine uses a system that enables clearance control during under-load operation based on the enhanced air-cooled system. This system uses two cooling air supply methods: one causes cooling air to bypass the turbine blade ring and introduces it directly into the combustor and the other causes cooling air to pass through the turbine blade ring in advance to supply it to maximize the performance by reducing the turbine clearance during load operation. These two systems can be switched by the switching valve (three-way valve) even during load operation. The former can handle operation with large load fluctuations by opening the clearance (Flexible Mode). On the other hand, the latter can close the clearance during load-hold operation and maximize the performance of steady operation (Performance Mode). **Figure 8** shows the behavior of the clearance when the three-way valve is switched during load operation. It was ultimately confirmed that this system can improve operability more than before while maximizing performance.

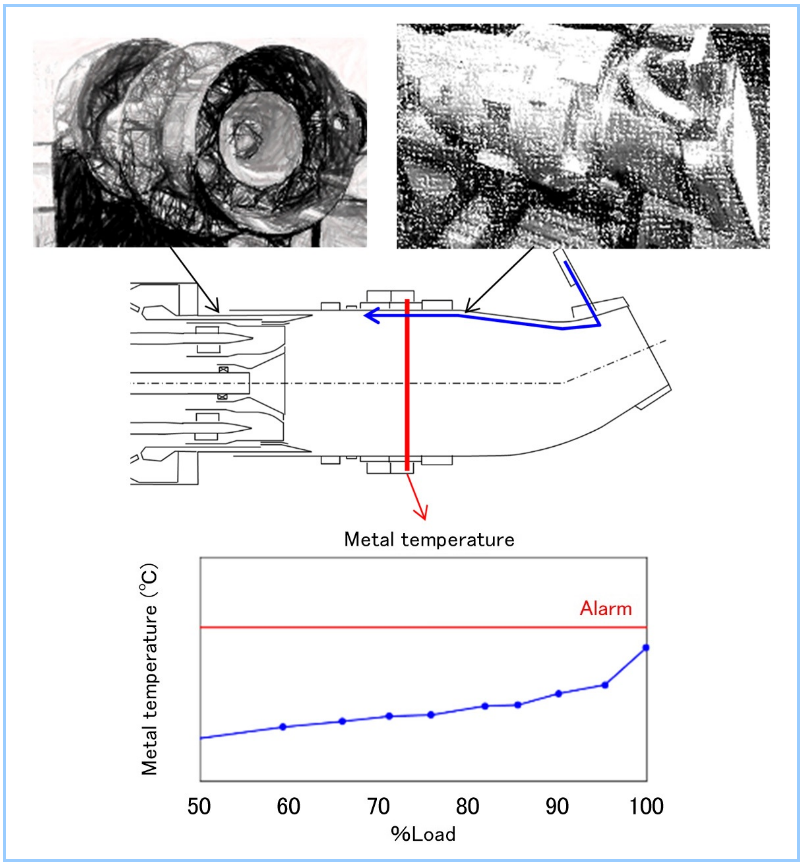

Figure 7 Measurement results of enhanced air-cooled combustor metal temperature

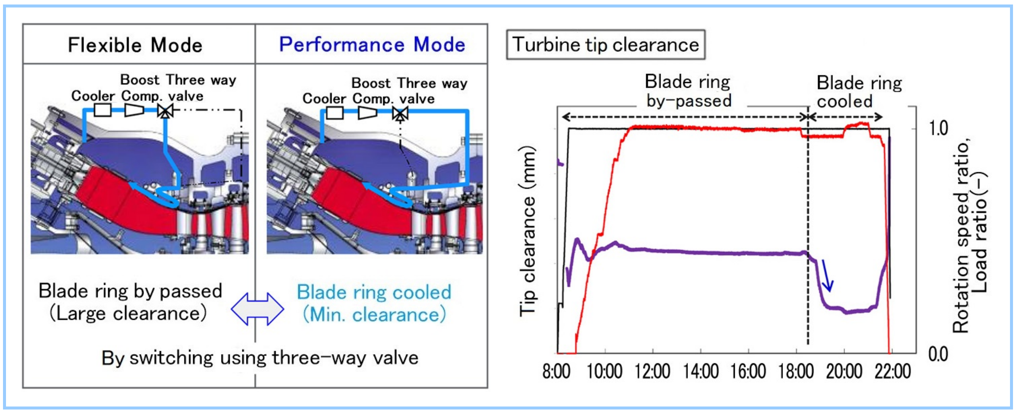

Figure 8 Turbine clearance control using enhanced air-cooled system

3.2 Turbine blade metal temperature

The turbine inlet temperature of the 1650°C class JAC series gas turbine can become 50°C higher than that of the J series and adopts a thicker TBC to achieve both high performance and reliability. As mentioned above, the integrity of the thicker TBC has been verified and confirmed at T-point over the long term. **Figure 9** shows the specially-measured metal temperature distribution of the JAC series turbine row 1 vane to which the TBC is applied in order to optimize the cooling design. It was confirmed that although the turbine row 1 vane was subjected to the strictest heat load and its cooling structure was complicated, there were no local high temperature parts, all parts were below the design allowance temperature and the integrity was maintained under the condition of an inlet gas temperature of 1650°C. The integrity was also confirmed in the inspection after operation.

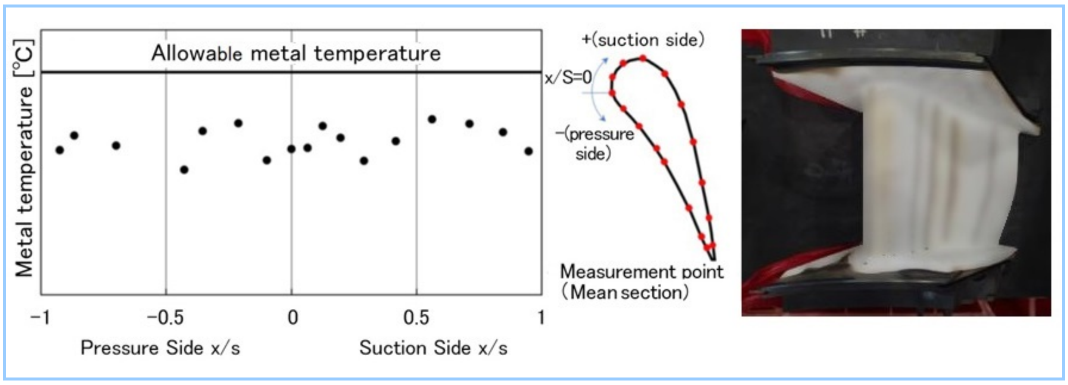

Figure 9 Metal temperature distribution measurement results of turbine row 1 vane and inspection results after operation

For the turbine row 1 blade, in addition to confirmation of the blade surface metal temperature and vibration stress using telemetric measurements, pyrometric measurement, which has been introduced at T-point, was carried out. The pyrometer was inserted into the gas path from the standby position through the insertion hole provided in the combustor casing and the turbine row 1 vane to confirm the integrity of the blade surface temperature distribution around the leading edge of the blade surface, which was subjected to a particularly high heat load. The integrity was also confirmed in the inspection after operation (**Figure 10**).

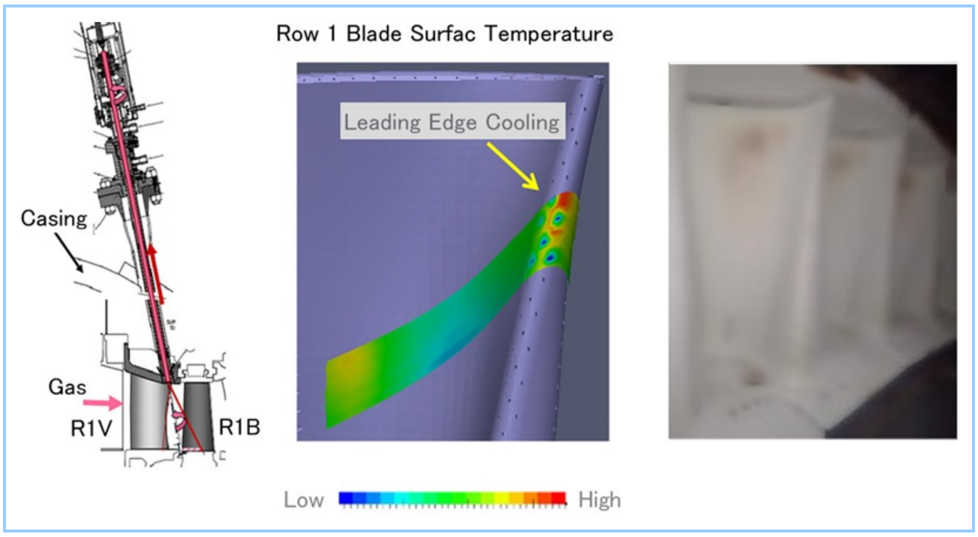

Figure 10 Surface temperature distribution measurement results of turbine row 1 blade and inspection results after operation

3.3 High pressure ratio compressor

The compressor of the 1650°C class JAC series gas turbine has a pressure ratio that was increased from 23 to 25. However, since a high pressure ratio compressor has a design in which the outlet flow path area is relatively narrow, there is a concern that the flow rate will decrease and the rotating stall will relatively deteriorate during startup with a low pressure ratio. As mentioned above, an H series compressor with a similar pressure ratio of 25 was validated, as was a compressor with a pressure rate of 25 based on the J series in May 2018 at T-point. Detailed temporary measurements were also carried out for the JAC series and it was ultimately confirmed that the starting characteristics, blade vibration stress and aerodynamic performance were favorable (**Figure 11**).

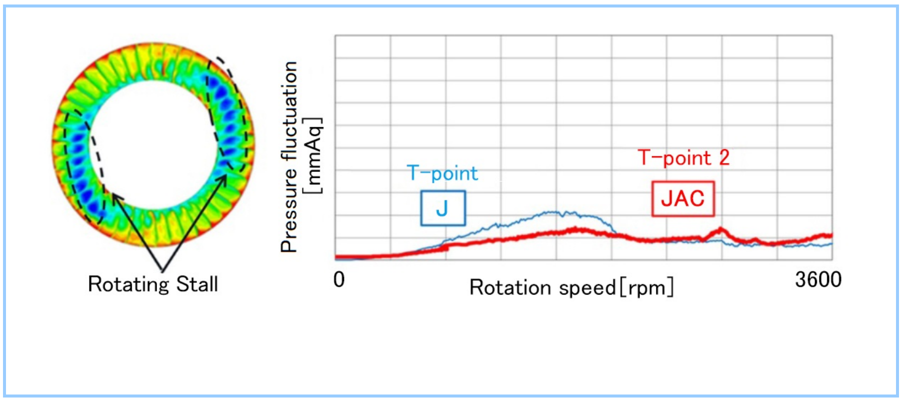

Figure 11 Verification results of JAC gas turbine high pressure ratio compressor

3.4 Status of gas turbine after one year of operation

Commercial operation commenced on July 1, following the test operation that started in January 2020. It has been confirmed that the components are sound after about one year of power supply operation and verification test operation, as a result of inspection of various parts including the compressor, combustor, turbine and inlet/exhaust systems and thus there is no problem in terms of the long-term reliability (**Figure 12**). After the completion of the verification test operation in the spring of 2021, power supply operation will be continued again and operational hours and the number of starts will be further accumulated to continuously confirm the long-term reliability.

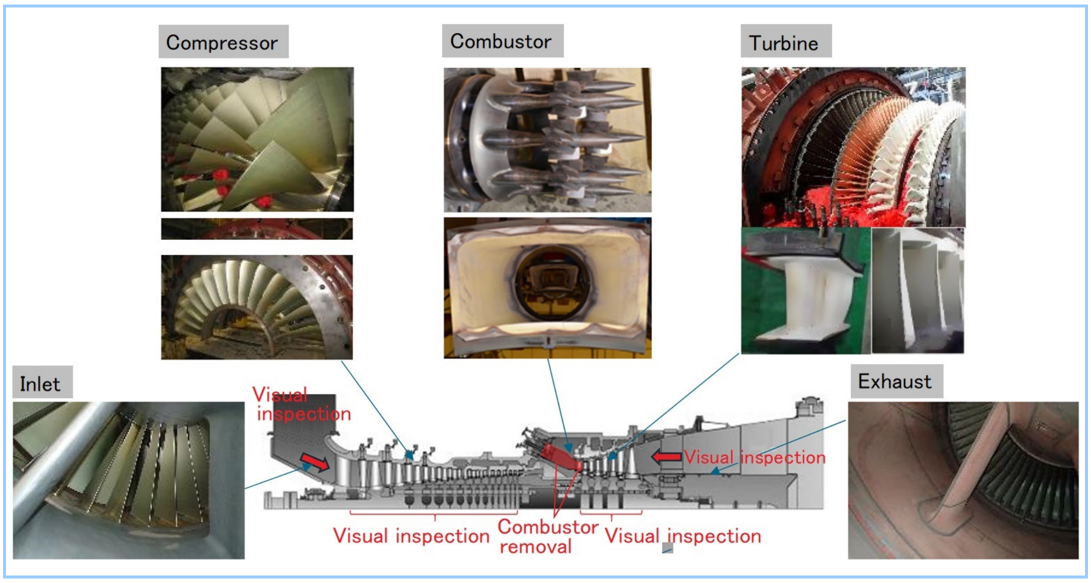

Figure 12 Overview of JAC series gas turbine inspection results in March 2021

3.5 Future development of JAC series gas turbine

As shown below, the construction and operation of customers' commercial plants using JAC series gas turbines that have been verified at our power plant demonstration facility T-point 2 and confirmed to offer long-term reliability as described above have commenced, striving steadily for realizing a more stable global energy supply. 60 Hz M501JAC gas turbines have been shipped to commercial plants in North America and other countries one after another since September 2020 and the local installation work is being carried out (**Figure 13**). The first of the eight 50 Hz M701JAC gas turbines for Thailand started operation on March 31, 2021, as scheduled despite the COVID-19 disaster. The construction work of the remaining units is progressing toward the start of operation of all turbines in 2024 (**Figure 14**).

Figure 13　Shipping of commercial 60 Hz M501JAC gas turbine

Figure 14　Operation start of commercial 50 Hz M701JAC gas turbine

4. Conclusion

For higher GTCC efficiency, a higher temperature of the gas turbine plays an important role. Mitsubishi Power has participated in the "1700°C class Ultrahigh-Temperature Gas Turbine Component Technology Development" national project since 2004. We utilized the results of these efforts to develop the high-efficiency M501J gas turbine, which attained the world's first turbine inlet temperature of 1600°C and we have since steadily accumulated operating results. In order to further improve the efficiency and operability of GTCC, we developed the next-generation 1650°C class JAC series gas turbine, which is based on the proven J series and uses an enhanced air-cooled system for cooling the combustor, a thicker TBC and a compressor with a high pressure ratio as its core technologies and completed the validation of the individual elements at the T-point demonstration facility.

We had been proceeding with construction of the second gas turbine combined cycle power plant demonstration facility (T-point 2) at our Takasago Works for long-term verification of the JAC series gas turbine. We started its test operation in January 2020, carried out as many as about 2,800 temporary large-scale measurements and made final confirmation of the integrity of the JAC series components, such as the reliability and performance during 1650°C operation. At T-point 2, the combined rated output reached 566 MW on April 2 and all the functional confirmations as a power generation facility were completed. Commercial operation commenced on July 1. Since then, both operational hours and number of starts continue to be accumulated in the operation according to the supply and demand requirements. It has been confirmed that the components after about one year of operation are sound and that they offer long-term high reliability.

Verified M501JAC gas turbines have been shipped to commercial power plants in North America, etc., one after another and the 50 Hz M701JAC gas turbine also started operation in Thailand in March 2021 as scheduled despite the COVID-19 disaster. Hydrogen co-firing is planned for a future GTCC power generation project in Utah in the United States. By incorporating our proprietary combustor technology, we aim to start the operation of the JAC series gas turbine with a hydrogen co-firing rate of 30% and to realize 100% hydrogen-fired operation in the future.

The long-term verification operation at T-point 2 is carried out from our RMC (remote monitoring center). We aim to improve the reliability of not only major equipment such as gas turbines, but also the entire plant including auxiliary equipment, validate various applications included in the "TOMONI" digital solution, such as shortening the startup time and automatically optimizing operating parameters and realize autonomous operation in the future.

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