High-efficiency Gas Turbine Development applying 1600°C class "J" Technology

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Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has continually contributed to global environmental protection, as well as to the stable supply of energy through the development of gas turbines based on abundant operational achievements and advanced technology research efforts. More recently, we have developed the M501J capable of achieving the world's first turbine inlet temperature of 1,600°C and even a thermal efficiency in gas turbine combined cycle (GTCC) of 61.5% or more, using developments attained in the national "1,700°C-Class Ultrahigh-Temperature Gas Turbine Component Technology Development" project we joined in 2004. Demonstrative operation started in 2011, using the demonstration equipment located within our Takasago Machinery Works, for later implementation of the accumulation of our global sales and operational record. Furthermore, based on the core technologies adopted in the M501J (60Hz unit), the M701J as the 50-Hz unit of the J Series was developed, and its shipment was completed after being tested at the factory. This paper relates to how these state-of-the-art high-efficiency gas turbines are developed and operated.

1. Introduction

A gas turbine combined cycle (GTCC) system, which is the most efficient and cleanest of all fossil fuel-based power generating facilities, has a great affinity for renewable energy because of its excellent load-absorbing capability. In addition, the intensity of its presence is further growing with increasing global demand for electric power, as well as with expanding supply sources of natural gas, such as that resulting from the exploitation of shale gas fields.

The higher temperature of a gas turbine plays an important part in the higher efficiency of GTCC, and MHPS developed a 1,150°C-class large-capacity gas turbine, the M701D, in the 1980s, while at a later time, we also developed the M501F with a turbine inlet temperature of 1,350°C in 1989, and a steam-cooled combustor-attached type, the M501G, with a turbine inlet temperature of 1,500°C in 1997 for subsequent successful and successive demonstration of high plant thermal efficiency/reliability and low pollution (**Figure 1**).

Thereafter, toward the much higher efficiency of the gas turbine, In 2004, MHPS joined a national project known as the "1,700°C-Class Ultrahigh-Temperature Gas Turbine Component Technology Development" in which, after making efforts for the development of the latest technologies necessary to realize higher temperature/higher efficiency, we successfully developed and demonstrated the M501J capable of achieving the world's first turbine inlet temperature of 1,600°C using developments attained in the national project. Further based on the core technologies

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adopted in the M501J (60Hz unit), we have developed the M701J as the J Series' 50Hz unit. We are also proceeding with parallel development of the M501JAC, in which an air-cooled combustor has been adopted together with J Series technologies, and its operability is better despite its well-maintained J-series gas turbine-equivalent performance.

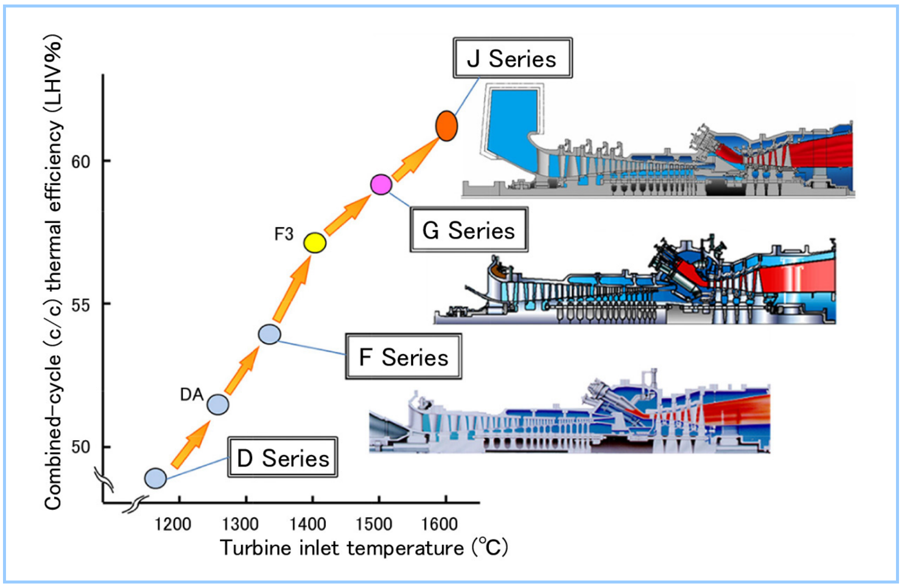

Figure 1 Developmental trend of large gas turbine models

Table 1 shows gas turbine performance and principal particulars. This paper relates to how these state-of-the-art high-efficiency gas turbines are developed and operated.

Table 1 Gas turbine performance (under ISO standard conditions) and principal particulars

	60Hz unit		50Hz unit
Series	M501J	M501JAC	M701J
Rotating speed	3600 rpm	3600 rpm	3000 rpm
GTCC output (generating-end)	470 MW	450 MW	680 MW
GT efficiency (lower heating value criteria)	41% or more	41% or more	41% or more
Compressor/pressure ratio	15 stages/23		
Combustor	Steam-cooled 16	Air-cooled 16	Steam-cooled 22
Turbine	Row 1-4 blade, air-cooled Row 1-3 vane, air-cooled Row 4 vane, uncooled		

2. Development and verification of M501J gas turbine

2.1 Development of M501J gas turbine

The M501J has made a turbine inlet temperature of 1,600°C achievable not only through the compilation of all component technologies already demonstrated in the F Series with a turbine inlet temperature of a 1,400°C class, as well as the G and H Series in the same 1,500°C class, all having abundant operational achievements, but also through the application of the most advanced 1,700°C-class technology developments attained in the national project. The higher turbine inlet temperature achieved and the state-of-the-art element technologies adopted bring much higher GTCC power-generating gross thermal efficiency than that of existing equipment. Moreover, if the conventional coal-fired thermal power plant is replaced with a natural gas firing J-series combined cycle counterpart, CO_2 emissions can be reduced by about 60 percent. **Figure 2** shows the technological characteristics of the M501J.

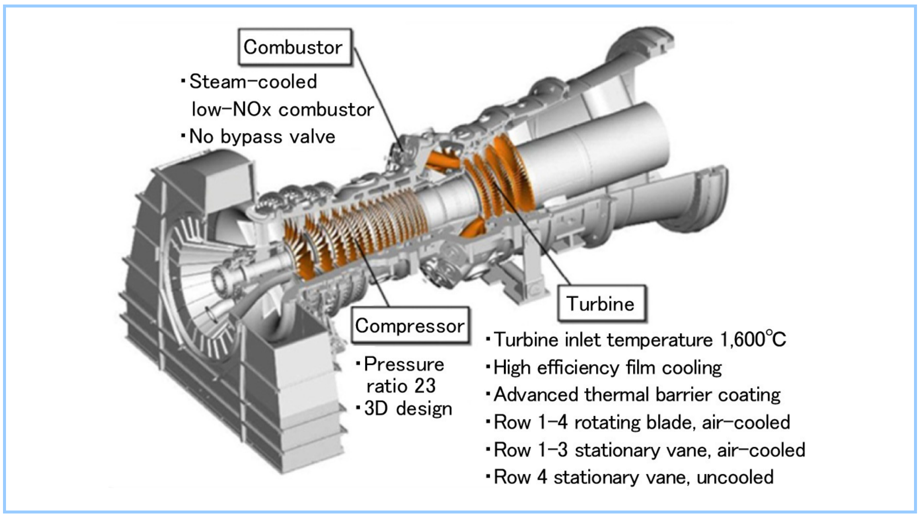

Figure 2 Characteristics of M501J gas turbine

2.2 Verification at in-house demonstration plant "T point"

In the development of the M501J, each component was verified at the basic design stage and test results were reflected in detailed design for final verification using actual power generation for the demonstration and subsequent production of commercial units.

Figure 3 shows an outside view of the equipment (known as T-point) located within MHPS Takasago Machinery Works to demonstrate a gas turbine combined cycle power plant. T-point was built as a combined cycle power plant for demonstration equipped with an M501G gas turbine, steam turbine, and heat recovery steam generator (HRSG), and its 39,253 hours of operation with 2,301 startups between January 1997 and October 2010 have made significant contributions to better performance, as well as to the higher reliability of the M501G.

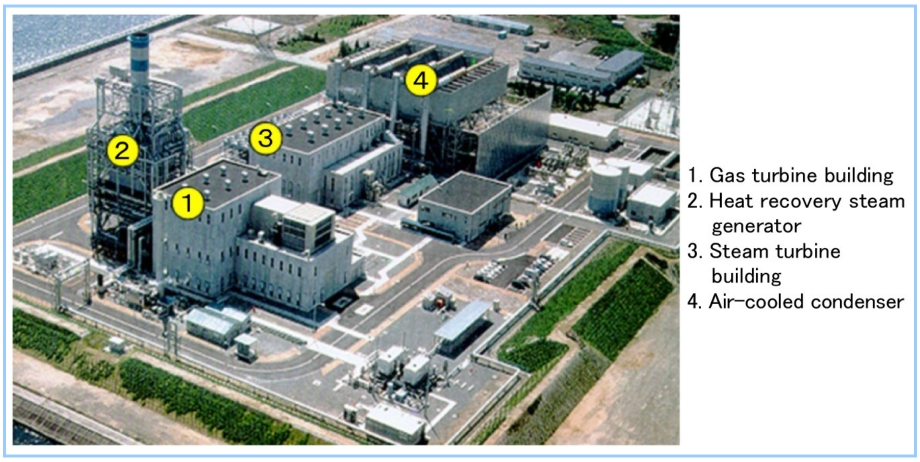

Figure 3 MHPS Takasago Machinery Works T-point demonstration combined-cycle power-plant

In October 2010, replacing the M501G with the M501J was executed and in February 2011, our first M501J unit started trial operation. Trial operation proceeded as scheduled, moving on to first spinning on February 2 and initial ignition on February 7, and a turbine inlet temperature of 1,600°C was reached only in the course of seven startups (**Figure 4**).

By the end of April thereafter, many different tests were conducted and disassembly inspections were made, finding the soundness of all parts and components. A special measurement of this first unit was taken at 2,300 points, finding that the performance, mechanical properties and combustion characteristics satisfied target values. At T-point, an M501J unit has been in operation since July 2011 to demonstrate its long-term reliability and as of the end of March 2015, 186 startups and 20,722 hours of operation have been marked, proving the steadiness in continual operation for demonstration. **Figure 5** shows October 2014's full-inspection results finding the soundness of all parts and components.

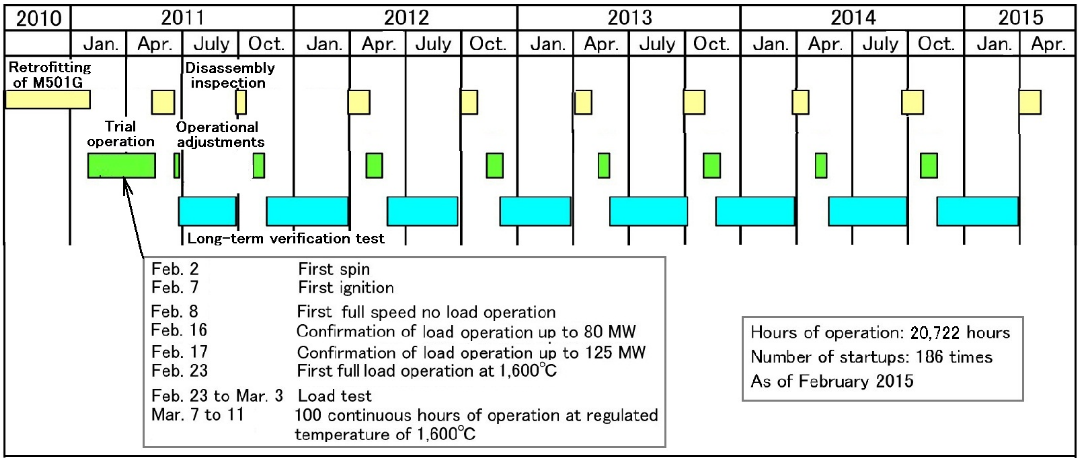

Figure 4 State of T-point demonstration equipment verification

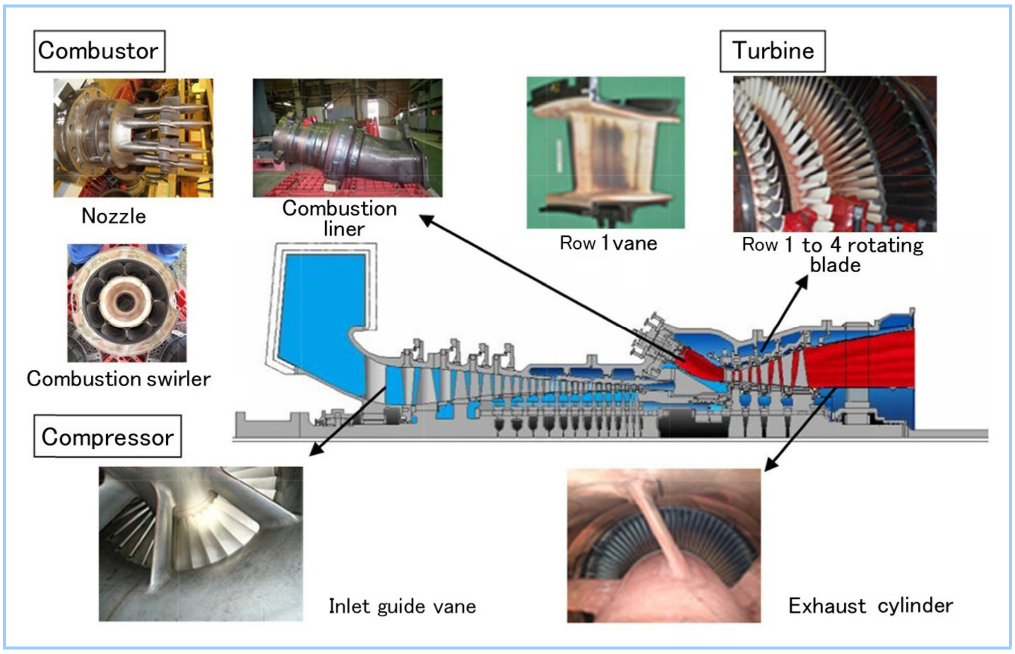

Figure 5 State of T-point demonstration equipment verification (18,466 hours of operation after 175th startup)

Meanwhile, the development and design of gas turbines in recent years has resorted to CFD or other large scale analysis-applied optimization tools in addition to element and prototype verification tests. In the analysis of the M501J's development design and verification results as well, these design tools are used effectively and the results of utilization are also reflected in the development of the high-efficiency gas turbines introduced in this paper, thus greatly contributing to the improvement of performance and reliability. **Figures 6** and **7** show the analytical results of the compressor's all-stage CFD, indicating such results have a good grasp of what actual equipment is like.

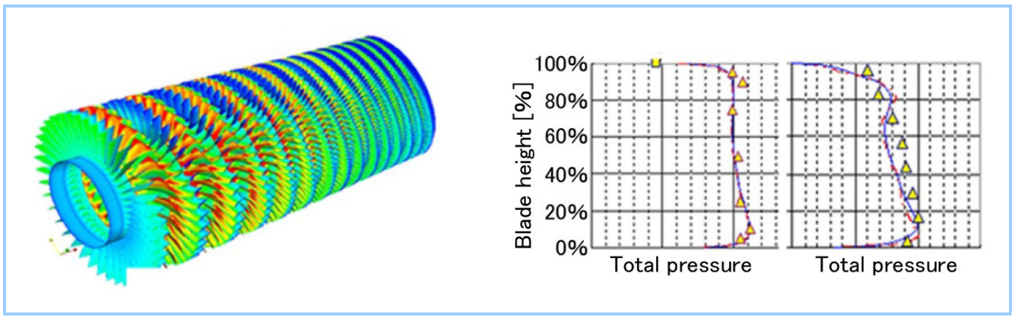

Figure 6 Actual compressor's all-stage CFD analysis and total pressure distribution (Left: 5-stage stationary vane inlet, right: diffuser inlet)

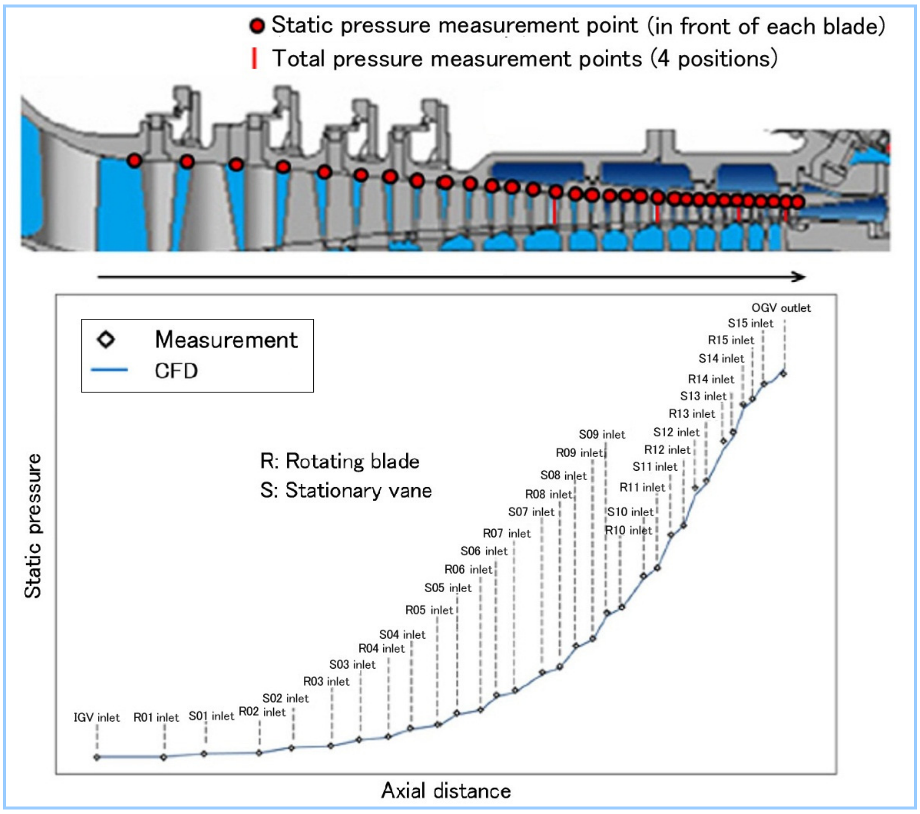

Figure 7 Actual compressor's all-stage casing surface pressure distribution (measurements vs. CFD)

3. Operational record of M501J gas turbine

As for the M501J demonstrated at T-point, orders have so far been received for a total of 34 commercial units, which were shipped one after another, and trial operation started in 2012 (**Figure 8**). Actual operational records have already been accumulated steadily at Kansai Electric Power's Himeji No. 2 power station and four South Korean power plants, reaching by now more than 110,000 hours of operation in cumulative total and 1,800 or more startups.

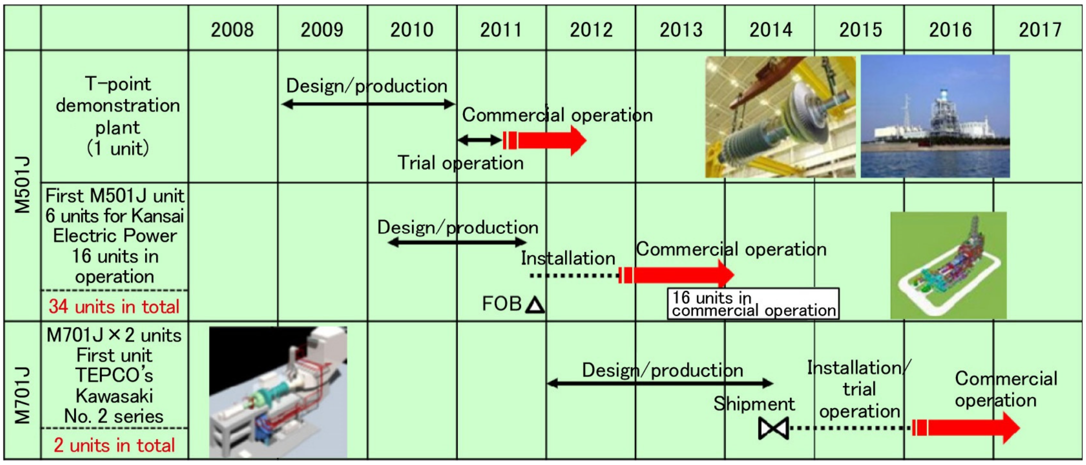

Figure 8 Operational schedule

At Kansai Electric Power's Himeji No. 2 power station, commercial operation of our first GTCC unit (a 501J gas turbine and a steam turbine combined for a rated output of about 486,500 kilowatts) started in August 2013, and thereafter, a total of six units entered commercial operation in succession, making Himeji No. 2 power station the largest thermal power plant of Kansai Electric Power with a total output of 2.919 million kilowatts (at atmospheric temperature of 4°C) (**Figure 9**).

In South Korea, orders have already been received for 14 M501J gas turbine units to meet electric power demand in the country, and among them, 10 units have started operation at 4 plants (as of March 2015, **Figure 10**) . In addition, there are orders for one unit of the M501J at home and

34 units of the same from countries such as South Korea and the United States. **Figure 11** shows the operational records of M501J gas turbines which have started commercial operation.

Figure 9 Whole view of M501J GTCC plant at Kansai Electric Power's Himeji No. 2 power station

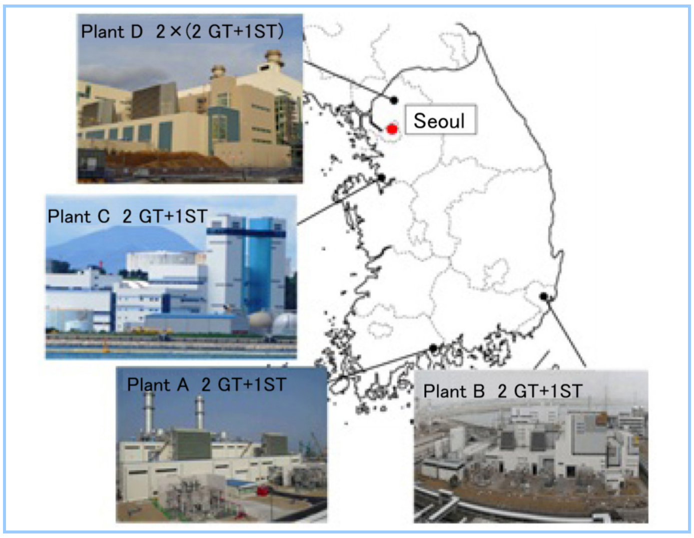

Figure 10 State of operation of South Korea's 501Js

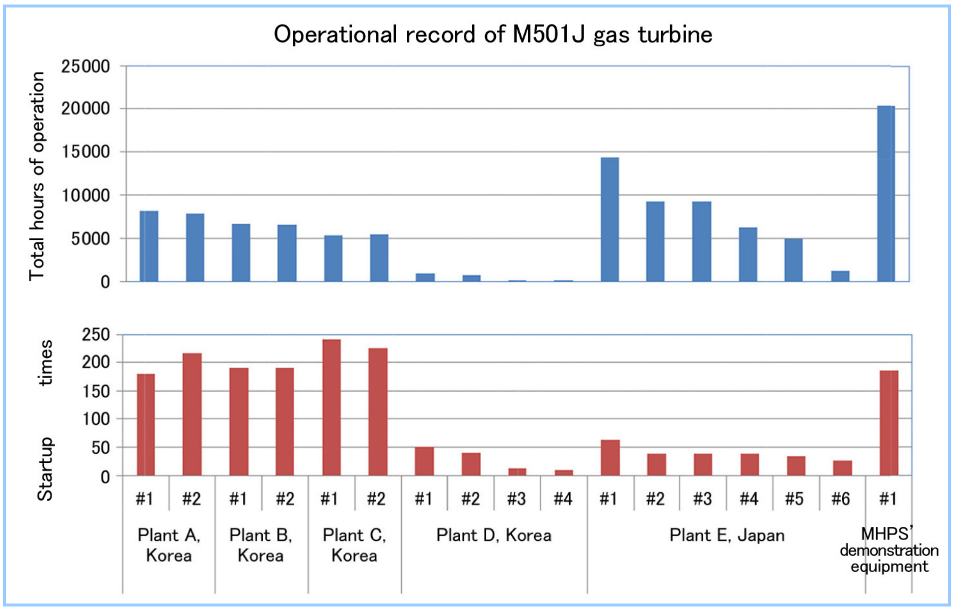

Figure 11 Operational record of M501J after commercial operation started (as of February 2015)

4. Other gas turbine development applying J-series technology

MHPS continually pursues high-efficiency gas turbine development based on core technologies adopted in the M501J, the high performance and high reliability of which have been successfully demonstrated. One example is the M701J as the 50Hz unit of the 1,600^{o}C-class J-series, and at present, the first unit to be marketed is under production. The development of the M501JAC with an air-cooled combustor adopted for better operability is also under way. The following relates to the characteristics of these high-efficiency gas turbines.

4.1 M701J gas turbine

The M701J (50Hz with a rotating speed of 3,000 rpm) was developed as a scaled unit of the M501J (60Hz with a rotating speed of 3,600 rpm) by applying a scaled-design concept with a reciprocal 1.2 times the rpm ratio as its scale ratio. That is to say, the designation of 1.2 times the M501J turbine's dimensions as the dimensions of the M701J establishes a similarity rule in design, maintaining stress, temperature and other characteristics at each part of the M701J equal to those of the M501J. On the other hand, since air flow and output are proportional to the square of the scale ratio, the GTCC output of the M701J is 680 MW, or about 1.44 times that of the M501J (Table 1). Shipments of the first units were completed within 2014, targeting the start of commercial operation in 2016 (**Figure 12**).

Figure 12 701J gas turbine at Tokyo Electric Power's Kawasaki power station

4.2 M501JAC gas turbine

The M501JAC is a gas turbine for which operability has been improved, with the M501J where steam is used to cool the combustor as a base, such as by adopting an air-cooled combustor that demonstrated a favorable operational record in the M501GAC and shortened the startup time, while maintaining a level of performance equal to that of the M501J. **Figure 13** shows the characteristics of the M501JAC. The compressor is the same as the M501J's. Although the turbine section's flow path is also identical in shape, the structure to cool the turbine's rotating blades and stationary vanes has been optimized to match the air-cooled combustor. The combustor adopted was an air-cooled one that demonstrated a favorable operational record in the M501GAC, and lower-NOx technology verified using the J-series was applied. The M501JAC is under development, aiming at the shipment of its first units in 2015, and the air-cooled combustor was verified, using T-point demonstration equipment in 2014.

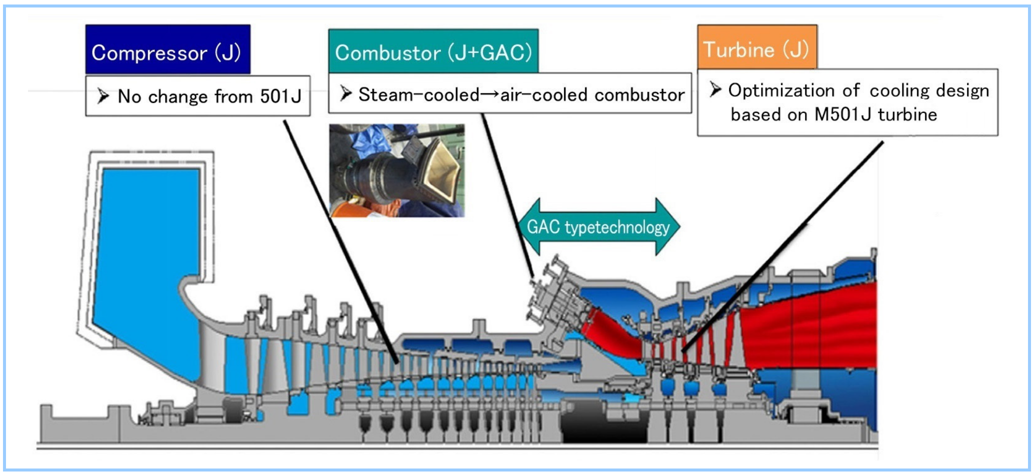

Figure 13 Characteristics of M501JAC gas turbine

5. Development of next-generation gas turbine

J-series gas turbines employ a steam cooling system in the combustor, but if it can be air-cooled, while keeping the turbine inlet temperature high, much higher efficiency, as well as better operability of GTCC, can be hoped for. This is why MHPS is engaged in next-generation GTCC development and started to develop element technologies for an air-cooled 1,650°C-class gas turbine including those for the closed (next-generation) air-cooling system being jointly studied with Tohoku Electric Power Co., Inc. targeting a higher turbine inlet temperature, and is making efforts toward the commercialization thereof in the 2020s, aiming for a combined cycle power generation efficiency of 63%.

Figure 14 shows a schematic of the next-generation closed air cooling system. This system is proposed as a cooling system in which the air extracted from the compressor outlet (combustor casing) is cooled by an outside cooling device, then further compressed by a boost-up air compressor and after being used for cooling the combustor, returned to the casing. The system can be characterized as follows:

(1) Available as a high-efficiency system by recovering waste heat into the bottoming cycle
(2) Capable of achieving cooling performance equal to or higher than that of a steam cooling system through the optimization of the combustor's cooling structure
(3) Able to make startup time shorter than that in steam cooling

We intend to verify this next-generation air-cooling system, using MHPS's demonstration equipment, continue with the development of an air-cooled 1,650°C-class gas turbine while applying it to a 1,600°C-class gas turbine and make continual plant design efforts for air-cooled 1,650°C-class gas turbine combined power generation equipment, targeting the commencement of demonstration from 2020.

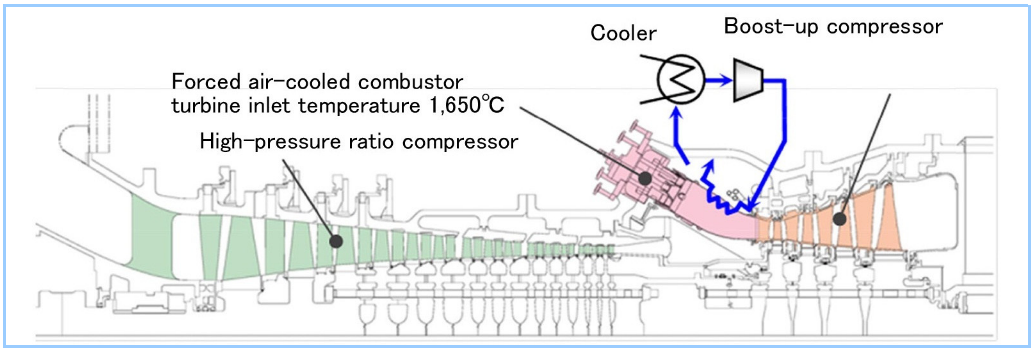

Figure 14 Characteristics of air-cooled closed gas turbine

6. Conclusion

Society has high hopes for gas turbine combined cycle (GTCC) as the cleanest and most efficient fossil fuel-based system of power generation that is excellent in terms of both the environment and economy. MHPS has successfully developed/demonstrated the M501J capable of achieving the world's first turbine inlet temperature of 1,600°C and even GTCC thermal efficiency of 61.5% or more, using developments attained in the national "1,700°C-Class Ultrahigh-Temperature Gas Turbine Component Technology Development" project we joined in 2004. In addition, the M701J and M501JAC are under development/production, based on derived core technologies. Further successive development of higher-efficiency counterparts with a 1,650°C-class closed air-cooled combustor is also under way. These gas turbines will, as high-efficiency equipment excellent in both performance and operability, continue to contribute to the stable global supply of electric power despite future concerns over the progress of the diversification and decentralization of electric power sources.

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