Development of 1600°C-Class High-efficiency Gas Turbine for Power Generation Applying J-Type Technology

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Mitsubishi Heavy Industries, Ltd. (MHI) has continued to contribute to the preservation of the global environment and the stable supply of energy through gas turbine development based on our abundant operating experience and state of the art technology. In recent years, using development results from the “1,700°C-Class Ultrahigh-Temperature Gas Turbine Component Technology Development” national project that MHI has participated in since 2004, we have successfully developed and verified the M501J, thereby capable of achieving the world’s first turbine inlet temperature of 1600°C and a gas turbine combined cycle (GTCC) thermal efficiency of 61.5% or more. Further based on the core technology employed in the M501J (60Hz unit), MHI developed the M701J as a 50Hz J unit. M501JAC, in which an air-cooling combustor was employed for better operational flexibility, is also under development. This paper presents how these advanced high-efficiency gas turbines are being developed and operated.

1. Introduction

Gas turbine-combined cycle (GTCC) power generation, as the highest efficiency and cleanest power generating system using fossil fuel, also has a high affinity for renewable energy due to its excellent load ramp rate capability. With the expansion of global demand for electric power and broadening supply sources of natural gas through actions such as shale gas field exploitation in the background, its presence is becoming greater and greater.

For higher GTCC efficiency, a higher temperature of the gas turbine has played an important role, and MHI developed the M701D, a 1,150°C-class, large-capacity gas turbine, in the 1980s. The company later developed the M501F with a turbine inlet temperature of 1,350°C in 1989, and the M501G, which employs a steam cooled combustor and has a turbine inlet temperature of 1,500°C in 1997. Through these developments, MHI has demonstrated high plant thermal efficiency and reliability, as well as low emission (Figure 1). Subsequently, aiming at further higher efficiency, MHI participated in the national project “1,700°C-Class Ultrahigh-Temperature Gas Turbine Component Technology Development” to grapple with development of the latest technology necessary for higher temperature/efficiency and using the results of such development, developed/demonstrated the capability of M501J to achieve the world’s first turbine inlet temperature of 1,600°C and GTCC thermal efficiency of 61.5% or more. Furthermore, based on the core technology used in the M501J (60-Hz unit), M701J was also developed as the 50-Hz unit the J. The development of M501JAC, in which operational flexibility was improved while maintaining the same level of performance as the J-type gas turbines by employing an air-cooled combustor in addition to J type technology, is also under way at the same time.

Table 1 shows gas turbine performance and main specifications. This paper describes how these state-of-the-art high-efficiency turbines are developed and operated.

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2. Development and Verification of M501J Gas Turbines

2.1 Development of M501J gas turbines

The M501J was able to achieve a turbine inlet temperature of 1,600°C through the compilation of component technologies already demonstrated by the operationally ubiquitous F type and G/H type, with turbine inlet temperature classes of 1,400°C and 1,500°C, respectively, as well as through the application of a national project that resulted in the development of the most advanced 1,700°C-class technology (Figure 2).

Figure 1  Changing development of turbine models

Table 1  Gas turbine performance (ISO's standard conditions) and main specifications

<table>
<thead>
<tr>
<th>Type</th>
<th>60Hz unit</th>
<th>50Hz unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotating speed</td>
<td>3600rpm</td>
<td>3600rpm</td>
</tr>
<tr>
<td>GTCC output</td>
<td>470MW</td>
<td>450MW</td>
</tr>
<tr>
<td>GTCC efficiency</td>
<td>61% or more</td>
<td>61% or more</td>
</tr>
<tr>
<td>Compressor/pressure ratio</td>
<td>15 stages/23</td>
<td></td>
</tr>
<tr>
<td>Combustor</td>
<td>Steam-cooled, 16 cans</td>
<td>Air-cooled, 16 cans</td>
</tr>
<tr>
<td>Turbine</td>
<td>Row 1-4 rotating blade, air-cooled</td>
<td>Row 1-3 stationary vane, air-cooled</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Row 4 stationary vane, non-cooling</td>
</tr>
</tbody>
</table>

Figure 2  Design concept of M501J gas turbine
The H type shown in Figure 2 is a 1,500°C-class gas turbine that also employs steam cooling in its turbine rotor-stator blades, and has been demonstrated employing a high pressure ratio compressor with a pressure ratio of 25. This increase in the turbine inlet temperature and the adoption of the latest component technology substantially raises the thermal efficiency compared with conventional units, and the M501J can achieve 61.5% or more (ISO’s standard conditions, low heating value-base) (Table 1). CO₂ emissions can be reduced by about 60% if a conventional coal-fired thermal power plant is replaced by a natural gas-fired J-type combined cycle power plant. The technical characteristics of the M501J shown in Figure 3 are described in the following:

![Figure 3  Characteristics of M501J-type gas turbine](image)

(1) Structural design features

The basic structure of the M501J is of the ubiquitous F and G type-based design, and has inherited characteristics including (a) a connection to the generator using a cold end drive method that is less affected by thermal elongation and that requires no flexible coupling, etc., (b) a rotor of the double-bearing structure that is supported by the compressor-side bearing and the turbine-side bearing, (c) an axial exhaust turbine that is best suited to the layout of a GTCC plant, and (d) a rotor structure that allows the transmission of the torque by bolt-jointing the torque pin-clipped disk with the compressor rotor and the curvic coupling-equipped disk with the turbine rotor.

(2) Compressor

The M501J compressor is a 15-stage axial flow type with a pressure ratio of 23, designed in accordance with the technology of the H-type compressor with a pressure ratio of 25. Advanced three-dimensional design has been applied for better performance, mitigating the shock loss in the front stage and friction loss in the middle-rear stage. After three-dimensional CFD-based evaluation, this concept was verified, applying the high-speed research compressor (HSRC, Figure 4) to a real machine-scale model. Air is bled from the three pressure stages – low, middle and high – while the compressor is in operation to control the inlet guide vane (IGV) and front 3-stage variable vane (VV), thereby limiting the occurrence of rotating stall while in operation and improving the partial load performance of GTCC.

(3) Combustor

The M501J combustor employs the closed steam cooling method successfully used in the G type. The turbine inlet temperature rose by 100°C from the G type’s 1,500°C to 1,600°C, but NOx reduction technology was applied, such as lowering the peak flame temperature in the combustion area through the improvement of combustor nozzle surrounding (Figure 5) for the purpose of more homogeneous fuel-air mixing, thereby limiting NOx emission concentrations to a level equivalent to that of the G type. The combustor was verified for its performance and reliability using cold flow, atmospheric pressure rig combustion and high pressure rig combustion tests, and this was reflected in its detailed design.
The turbine is a highly loaded 4-stage axial flow type for high performance. In addition to the fully three-dimensional design so far employed in the G type for better performance, the turbine aerodynamic technology developed in the national 1,700°C-class gas turbine project was applied. That is, considering such matters as flow field intervention and the effects of a horse shoe vortex from the front edge of the blade, we employed a non-axisymmetric endwall contouring that limits the secondary flow generated on the endwall area. As for the temperature increase from the G type, the technology developed in the national project was applied, enabling a conventional equipment-level metal temperature to be maintained. Of the 100°C gas temperature increase, about 50°C depends on improved turbine cooling technology and about 50°C on advanced thermal barrier coating (advanced TBC) (Figure 6).

Air cooled blades are used for turbine row 1-4 (rotating) blades and row 1-3 (stationary) vanes. Row 4 blade of the G type was an uncooled blade, but the J type’s was cooled due to an increase in turbine inlet temperature. The blade material employed was MGA1400 (Mitsubishi Gas Turbine Alloy 1400) for the rotating blades and MGA2400 for stationary vanes, with the row 1-3 rotating blades being of directional solidification. MGA1400/2400 has already been employed in F and G types.
As shown in Figure 7, the cooling structure has been upgraded each year to the F and then to the G type, and the J type has, as mentioned earlier, employed high performance film cooling and advanced TBC as improved turbine cooling technology developed in the national project. As for high performance film cooling, after the film shape was optimized through component tests of a flat plate (Figure 8) and film efficiency was verified by low-speed rotating turbine (LSRT) and medium pressure cascade tests, it was employed in the M501G at T-point and its validity was confirmed. The results of these tests were reflected in the design of the J type’s turbine blade and the high pressure/hot cascade test was followed by the final test using the first unit of M501J. Advanced TBC was applied to the T-point M501G turbine blade and after long-term verification experiments, high pressure/hot cascade tests of the J-type turbine blades were conducted for verification.

2.2 Verification using T-point power generation demonstrator

In the development of the M501J, verification tests were conducted for each component at the stage of basic design to reflect the results in the detailed design and finally, after verification experiments using a power generation demonstrator, the commercial unit was manufactured.

Figure 9 shows the appearance of a gas turbine combined cycle power plant demonstrator (T-point) located within the MHI Takasago Machinery Works. At T-point, a combined cycle power plant equipped with a M501G gas turbine, a steam turbine and a heat recovery steam generator (HRSG) built as a demonstration unit underwent 39,253 hours of operation and 2,301 starts/stops from January 1997 to October 2010, greatly contributing to the improved performance and higher reliability of the M501G.
From October 2010, work to replace the M501G with the M501J was under way and in February 2011, the first M501J unit started trial operation. Trial operation proceeded as scheduled and after the first spin on February 2, the first ignition on the 7th day of the same month and only 7 starts/stops, the turbine inlet temperature of 1,600°C was reached (Figure 10). Thereafter, various tests were conducted and overhaul inspections were carried out, and each component and part was determined to be sound. This first unit was subjected to a special 2,300-point measurement, verifying its performance, mechanical properties and combustion characteristics to satisfy the target values. As an example, Figure 11 shows the blade surface metal temperature distribution of a row 1 stationary vane. With respect to the platform and blade surface of a turbine row 1 rotating blade, the surface metal temperature distribution was measured using a pyrometer. Figure 12 shows a measurement result of the metal temperature of the rotating blade platform.
In addition, the design of gas turbines in recent years features, in addition to component tests and verification experiments, optimization design to which large-scale analysis including CFD is applied. These design tools were used effectively not only for the design stage of the M501J, but also for the analysis of the verification results, and the utilization of such results is reflected in the development of the high-efficiency gas turbines cited in this paper, greatly contributing to the improvement of performance and reliability. Figure 13 and Figure 14 show examples of compressor/turbine full stage CFD analysis results, and it is apparent that CFD analysis results reasonably agree with the measurement results.
From July 2011, operation to demonstrate the long-term reliability of M501J was under way at T-point, reaching 10,548 hours of continuous operation with 120 starts/stops at the end of March 2013, and demonstration operation steadily continues. Figure 15 shows the results of major overhaul inspections in March 2013, where each component and part was found to be sound.

![Figure 15](image)

**Figure 15** T-point M501J major overhaul inspection results (March 2013, 10,548-Hour Continuous Operation, 120 Starts/Stops)

### 3. J-type technology applied to gas turbine development

Sixteen units of the commercial M501J demonstrated at T-point have been ordered so far, and commissioning of the first commercial unit completed in the summer of 2013 and started the commercial operation (Figure 16).

![Figure 16](image)

**Figure 16** Operation schedule

Based on the core technology employed in the M501J, for which excellent performance and high reliability were demonstrated, MHI is continually engaged in the development of high-efficiency gas turbines. One of such example is the M701J as the 1,600°C-class J type's 50Hz unit and the production of its first unit is currently under way. Development of the M501JAC, the operational flexibility of which was improved by employing an air-cooled combustor, is also taking place. The characteristics of these high-efficiency gas turbines are described in the following:

#### 3.1 M701J gas turbine

The M701J (rotating speed: 3000rpm, 50Hz) as a scaled version of the M501J (rotating speed: 3600rpm, 60Hz) was developed by applying the full-scale design concept with the rpm’s reciprocal value of 1.2 against 1 as the scale ratio (Figure 17). Namely, with the size of M701J taken as the 1.2-time scale of the size of M501J, similarity design rules become effective, thus keeping the stress, temperature and other characteristics of each M701J part similar to those of the M501J. On the other hand, since air flow and output are proportional to the second power of the scale ratio, M701J type’s GTCC output is 680MW, or about 1.44 times that of the M501J (Table 1). The shipment of its first unit of the M701J is scheduled in 2014.
3.2 M501JAC gas turbine

The M501JAC is a gas turbine which, based on the M501J employing steam cooling for the combustor, employs the air-cooled combustor successfully used in the M501GAC and offers improved operational flexibility, such as by shortening the starting time while maintaining the same level of performance as that of the M501J (Figure 18).

Figure 19 shows the characteristics of the M501JAC. The compressor is the same as that of the M501J. The flow pass design of the turbine area is also the same, but the cooling structure of the turbine rotor/stator blade is optimized in line with the air-cooled combustor employed. The combustor adopts the air-cooling system successfully used in the M501GAC and the low NOx technology verified using the J type was applied. The M501JAC is under development aiming at the first unit shipment in 2015, and in 2014, an air-cooled combustor is expected to undergo verification with the T-point demonstrator.
4. Conclusion

Gas turbine combined cycle (GTCC) power generation is both environmentally and economically friendly as the cleanest high-efficiency power generating system using fossil fuel, and is a technology for which society has great hope. Using the results of the “1,700°C-Class Ultrahigh-Temperature Gas Turbine Component Technology Development” national project that MHI has participated in since 2004, we have successfully developed/demonstrated the M501J, which is capable of achieving the world’s first turbine inlet temperature of 1600°C and GTCC thermal efficiency of 61.5% or more. In addition, based on such core technologies, MHI is proceeding with the development/production of the M701J and M501JAC. These gas turbines, amid further diversification/decentralization of power sources, will continue to contribute to the stable global supply of electric power as high-efficiency equipment offering both good performance and operational flexibility.

References