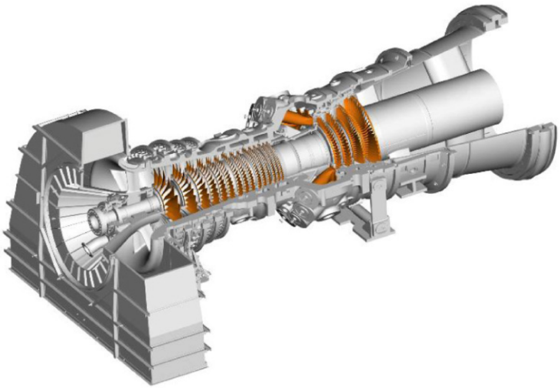
Key Technologies for Ultra-High Temperature Gas Turbines



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Gas turbine combined power generation can coexist with renewable energy and nuclear power generation as the cleanest and most economical form of thermal power generation facility, and therefore its long term market expansion can be expected. For further improvement in performance, the technology development of a 1700°C-class gas turbine is under way as a national project, and some of the latest developed technologies have been immediately applied to the development of the J type, which is the world's first 1600°C-class gas turbine. This paper gives a brief description about the development of the technologies that are targeted for application in next-generation gas turbines.

1. Introduction

Today, the requirement to reduce greenhouse gas emissions is an important issue. With such a background, the research on technologies for 1700°C-class gas turbines is moving forward as a national project, aiming at the practical application of a highly efficient thermal power generation technology using an ultra-high temperature gas turbine for advanced natural gas usage.

Figure 1 shows the technology development roadmap for realizing ultra-high temperature gas turbines. In the past, we implemented the first step that aimed at the technology development of six elements (shielding coating, cooling technology, combustor, turbine, compressor and heat-resistant material) of a 1700°C-class gas turbine from 2004 to 2007. The second step aimed at practical application from 2008 to 2011. The results of this project were reflected in the development of the 1600°C-class J-type gas turbine.

Recently, we have been proceeding with the third step of technology development that includes more than ten items targeting the development, manufacturing and test runs of practical equipment as shown in **Figure 2**.

This paper introduces the development status and past outcomes of some (eight items shown in Figure 2) of these cases.

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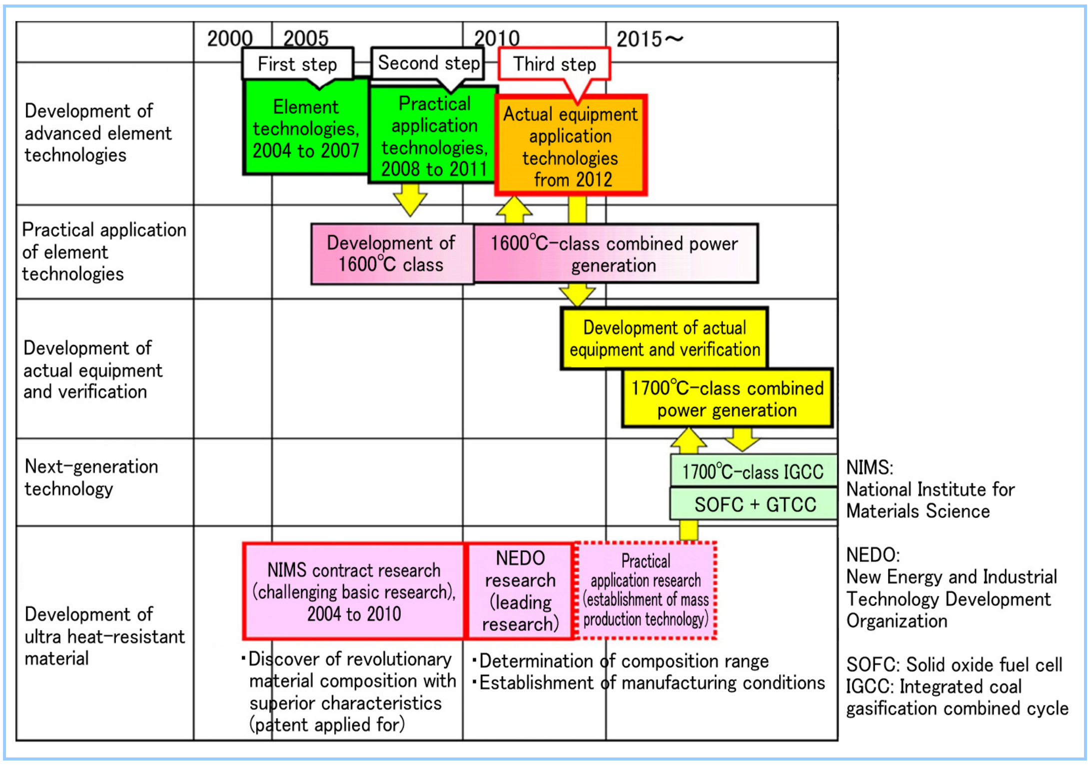

Figure 1　Technological development roadmap for ultra-high temperature gas turbines

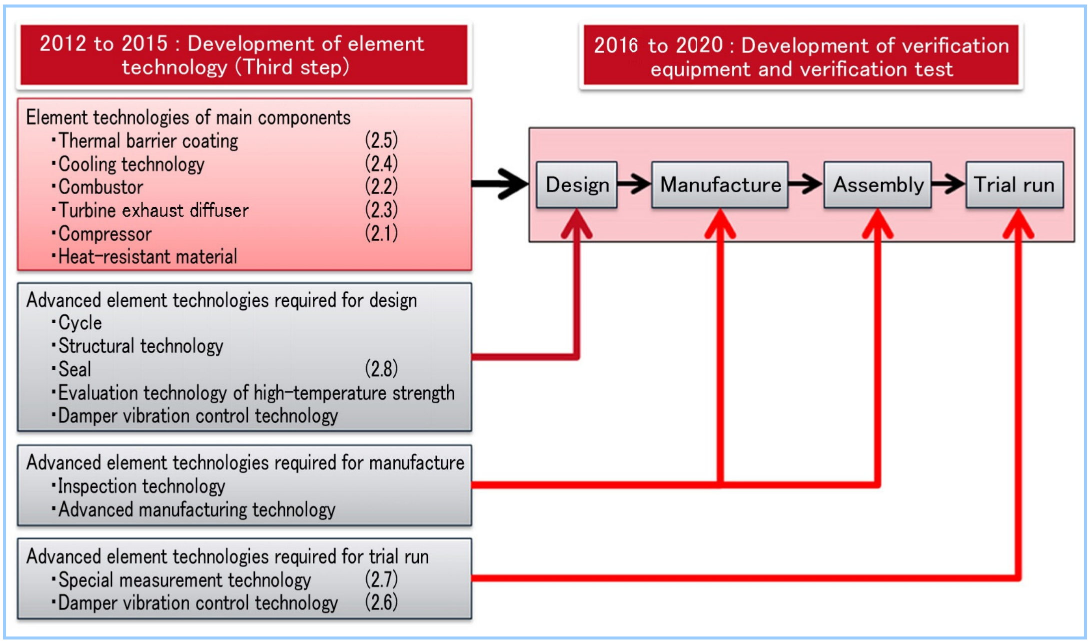

Figure 2　Development element of ultra-high temperature gas turbines

2. Element technologies of ultra-high temperature gas turbines

2.1 Development of boundary layer control high-performance compressor

1700°C-class gas turbine compressors require an improvement in the pressure ratio in order to optimize the cycle efficiency in response to an increase in the turbine inlet temperature. If such an improvement in the pressure ratio were realized using the conventional number of stages and shaft length, the compressor blade loading would have to be increased which would result in an increase in loss due to the development of the boundary layer, the deterioration of the surge margin and a decrease in startup stability. Therefore, to achieve both improvement in the pressure ratio and high performance/high reliability, it is necessary to consider the optimization of the three-dimensional blade shape using numerical flow analysis on all the stages to simulate the relevant flow details, and to verify the effects of blading improvements using a scale model test compressor.

Conventional verification tests use a three-stage or four-stage test compressor, but recently a scale model compressor that includes the front eight stages is under construction. This test rig will be used for verification of the improvement effect due to a change in the blade shape in consideration of the end wall boundary layer development in ~~a~~ the multi-stage compressor (**Figure 3**). This test facility has variable stationary vanes and thus, in addition to the evaluation of the performance improvement, evaluation of an idea to suppress unstable phenomena such as rotating stall at startup is also planned.

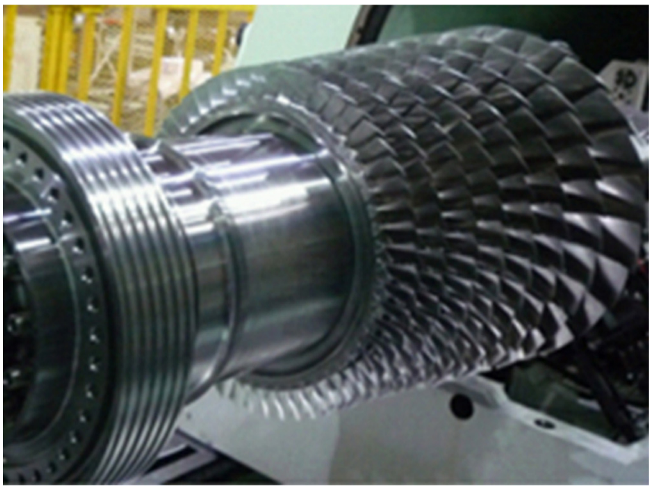

Figure 3 Overview of front eight-stage compressor test equipment

2.2 Technology for evaluation of combustor unsteadiness

One effective method to improve the cycle efficiency is to increase the turbine inlet temperature, but this leads to an increase in NOx emissions. For a decrease in NOx, a lean premixing combustion method is effective countermeasure, but premixing combustion results in unstable flame positioning and tends to generate combustion oscillation caused by the fluctuation of heat generation. Therefore the suppression of combustion vibration is an important design issue in the development of a premixing combustor, in addition to a decrease in NOx by making the premixed gas leaner and more uniform. As a technology for the evaluation of combustion vibration of an actual combustor, we are developing flame visualization using the OH-PLIF (OH planer laser induced fluorescence) method, which is an in-situ optical measurement technique, and an evaluation method utilizing the technique. The visualization of flame was conducted and the response of flame fluctuation to the phase of the pressure fluctuation was evaluated in an atmospheric pressure combustion test using a full-scale combustor.

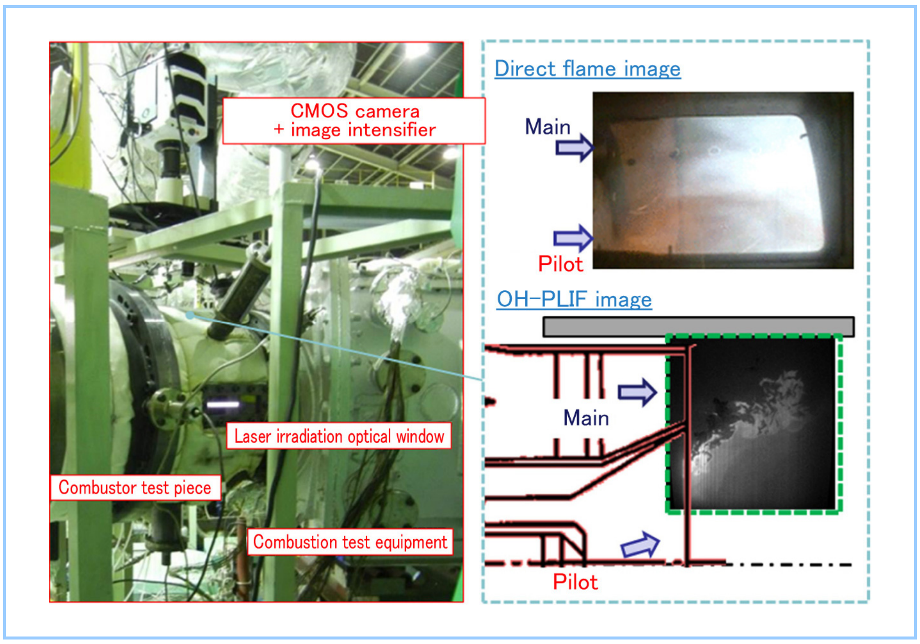

Figure 4 Test equipment and measurement example

Figure 4 shows an overview of the test equipment and measurement examples. **Figure 5** presents flame images obtained through the measurements. The Rayleigh index in the figure represents the correlation between the pressure fluctuation caused by combustion vibration and flame fluctuation, and the red area corresponds to the region where the combustion vibration is driven. From the results, an unstable combustion region where combustion vibration is driven under large combustion vibration conditions could be identified.[1] This evaluation technology is being used to elucidate the cause of combustion vibration.

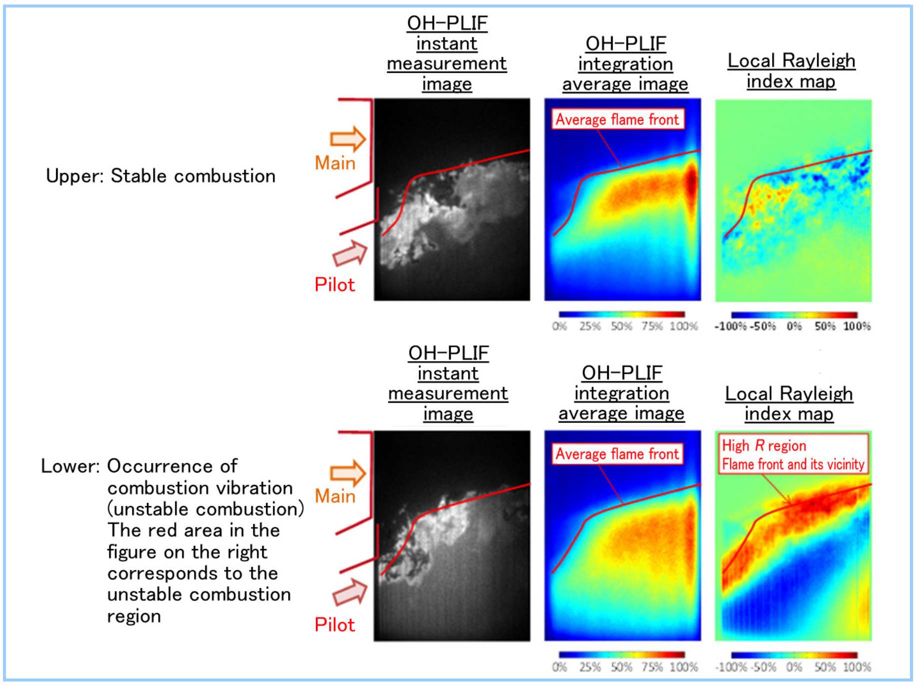

Figure 5 Flame measurement results using laser in actual combustor

2.3 Performance improvement of turbine exhaust diffuser

A turbine exhaust diffuser has a structure where the flow path area becomes larger toward the downstream. This allows the flow to slow down and the static pressure to be recovered. As a result, the static pressure at the outlet of the final stage rotor blade becomes lower than the atmospheric pressure, which improves the turbine efficiency due to an increase in the actual turbine pressure ratio (expansion ratio) and output. Because of decelerating flow at the exhaust diffuser, however, flow separation tends to occur. For the design of a high-performance diffuser shape, a technology for the accurate prediction of the flow inside the diffuser is required. For this reason, Research & Innovation Center of Mitsubishi Heavy Industries, Ltd. (MHI) applied advanced large-scale flow analysis to the annulus design (**Figure 6**) to optimize the internal flow of the turbine and diffuser in an integrated manner. This allows increased suppression of flow separation in the exhaust diffuser and a further reduction of exhaust flow speed (recovery of static pressure) simultaneously, resulting in significant improvement in performance. This technology, the effectiveness of which has been verified by detailed flow measurement in a diffuser test (**Figure 7**), is applied to the design of the turbine blade and exhaust diffuser of the J-type gas turbine.

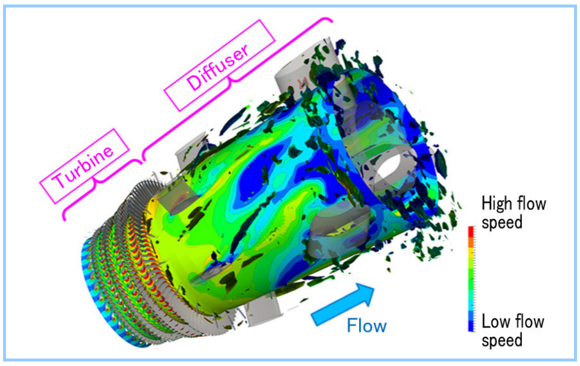

Figure 6 Large-scale flow analysis of internal flow of turbine exhaust diffuser

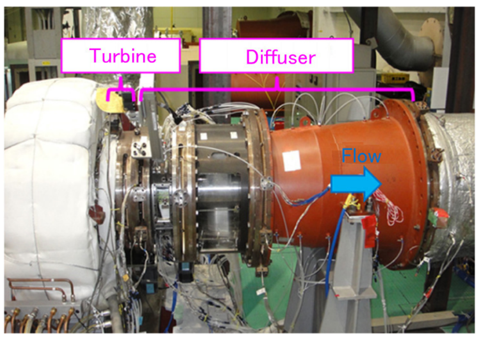

Figure 7 Turbine exhaust diffuser test equipment

2.4 Latest turbine heat transfer coefficient measuring technique

Turbine blade cooling design requires accurate surface distribution data of the heat transfer coefficient. In the past, the heat transfer coefficient was measured using a thin film heater and thermocouple (steady method). The steady method has a disadvantage in that it is a point measuring method, is high cost and requires a long time for measurement preparations. As such, we have developed a technology that allows the surface distribution of the heat transfer coefficient to be measured at a low cost and requires less preparation time using a combination of a main stream heater and an infrared camera (unsteady method). The unsteady method can obtain the surface distribution of the heat transfer coefficient by heating the main stream in a stepped manner and measuring the surface temperature change in the heated test piece using the infrared camera (**Figure 8**).

Figure 9 compares the results of heat transfer coefficient measurement between the steady method and the unsteady method. The unsteady method provided measurements similar to the steady method, and its effectiveness was verified.[2] The surface distribution of the heat transfer coefficient obtained using this measurement technology allows the design of cooling in response to local heat load, and contributes to the improvement of performance due to the reduction of cooling air.

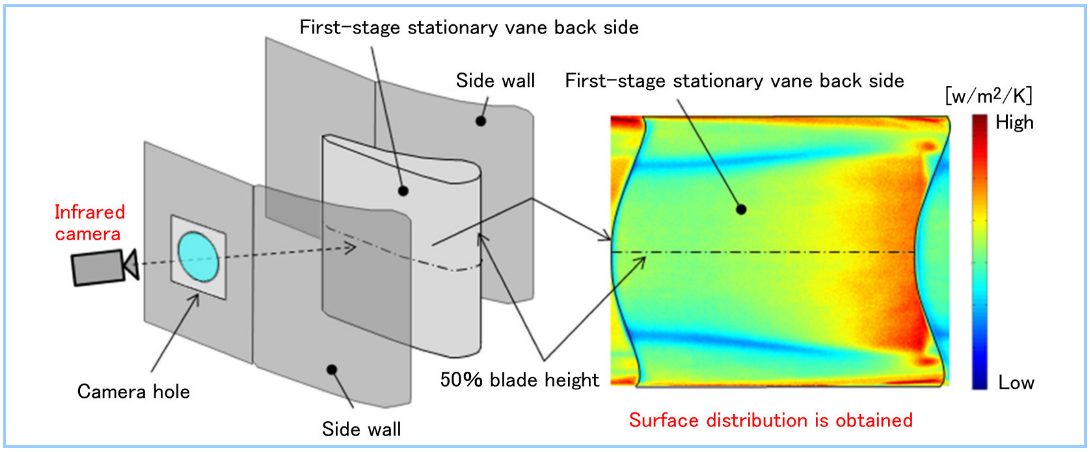

Figure 8 Example of heat transfer coefficient measurement using unsteady method (turbine vane suction side)

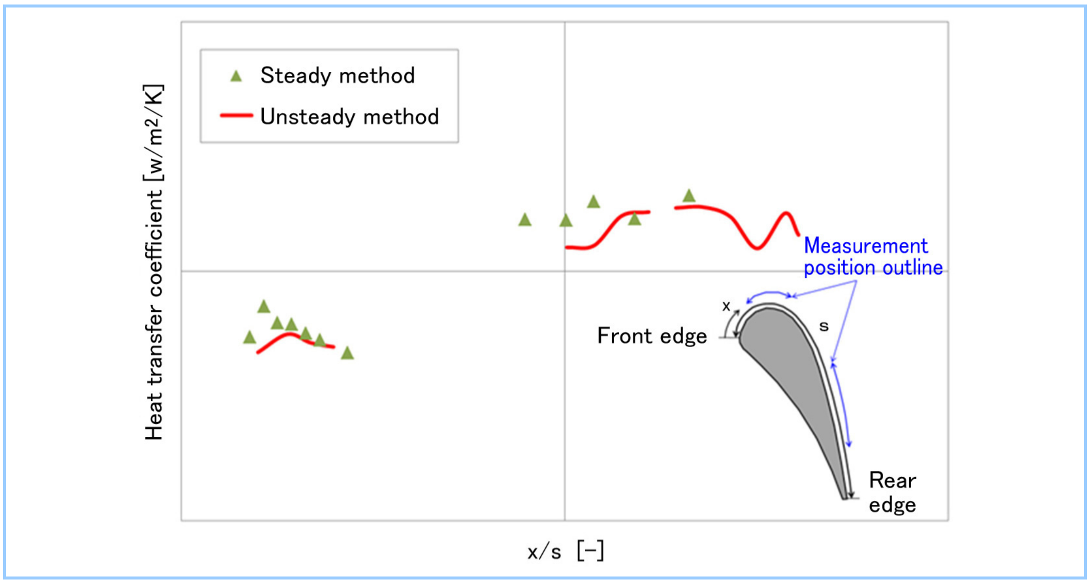

Figure 9 Comparison of heat transfer coefficient measurement results between steady method and unsteady method (turbine vane suction side surface, 50% blade height position)

2.5 Development of advanced thermal barrier coating

The advanced thermal barrier coating (TBC) uses materials with low thermal conductivity and superior high-temperature phase stability, candidates of which were sought and selected using a proprietary electronic structure-based material calculation system in a theoretical and analytical manner, in contrast to the conventional development technique using trial and error. This calculation system was developed by MHI Research & Innovation Center. For the extracted ceramic material, thermal spray powder manufacturing technology was created, and then thermal spraying technology was developed. The speed distribution and the temperature distribution of thermal flying sprayed particles affect the microstructure of TBC, and accordingly such distributions were measured. The thermal barrier effect and thermal cycle durability were evaluated. In addition, high-temperature erosion test equipment was developed and the characteristics were evaluated.[3] As a result, the spray conditions for advanced TBC that has these characteristics in a well-balanced manner were selected (**Figure 10**). Furthermore, a thermal spraying program that allows uniform and favorable coating thickness distribution of even a complex actual blade shape to be realized was developed through the utilization of a robot simulation. Advanced TBC that has the thermal barrier performance, durability and erosion resistance obtained through the series of research and development efforts was applied to a 1600°C-class M501J-type gas turbine from 2011 for the evaluation of long-term durability using actual power generation equipment (T-point) installed at the Takasago Machinery Works of Mitsubishi Hitachi Power Systems, Ltd. After long-term operation exceeding 10,000 hours, a major inspection was performed for the soundness verification of each of the parts in March 2013, and the conclusion that the advanced TBC had good thermal barrier performance and durability under actual equipment operating conditions[3] (**Figure 11**) was reached.

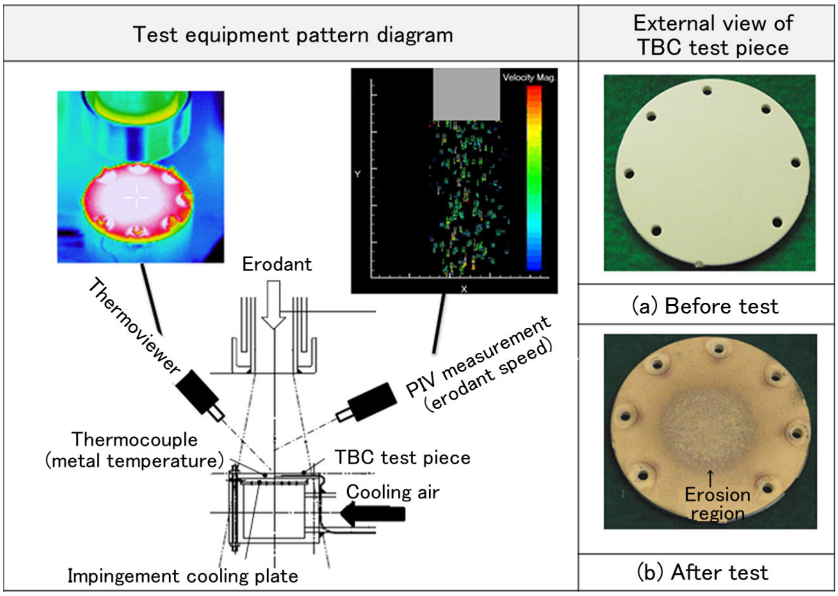

Figure 10 TBC high-temperature erosion test equipment

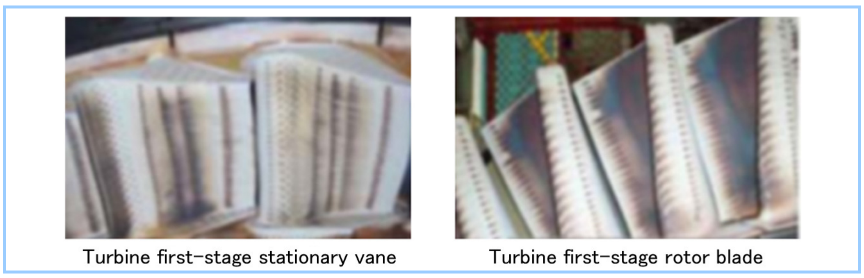

Figure 11 T-point M501 J-type inspection results (March 2013)

2.6 Turbine blade vibration characteristic prediction analysis technology

For a 1700°C-class ultra-high temperature gas turbine, blade vibration characteristic evaluation technology is more important than ever before because the fluid force applied to the turbine blade by high-temperature gas increases and thus conditions become more severe in terms of the vibration strength. The turbine rotor blade has a seal pin damper structure through which damping is obtained by friction between the blade and the seal pin, and the accurate prediction of the vibration characteristics is the key to the enhancement of reliability. We have introduced a concept of the contact length ratio that combines the micro contact and the macro contact, and are proceeding with the development and verification of a prediction analysis technology that takes into account the contact state with friction between the blade and the seal pin through estimation of the seal pin rigidity in addition to the Mindlin theory and the Hertz contact theory (**Figure 12**).

We are also working on accuracy improvement in CFD prediction of the blade row interference response by measuring the pressure fluctuation on the rotor blade surface in detail and an examination and evaluation of the occurrence mechanism of rotor blade exciting force (exciting force caused on the rotor blade) generated by the upstream vane interaction. With the latest CFD code, the amplitude and phase of the exciting force caused by the pressure fluctuation on the rotor blade surface can be accurately predicted (**Figure 13**).

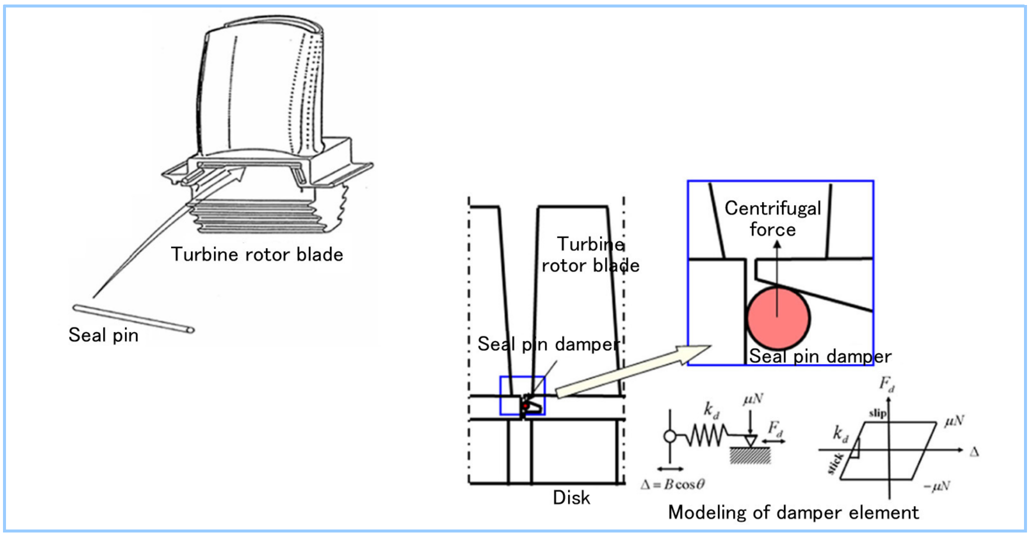

Figure 12 Prediction of vibration characteristics of seal pin damper blade

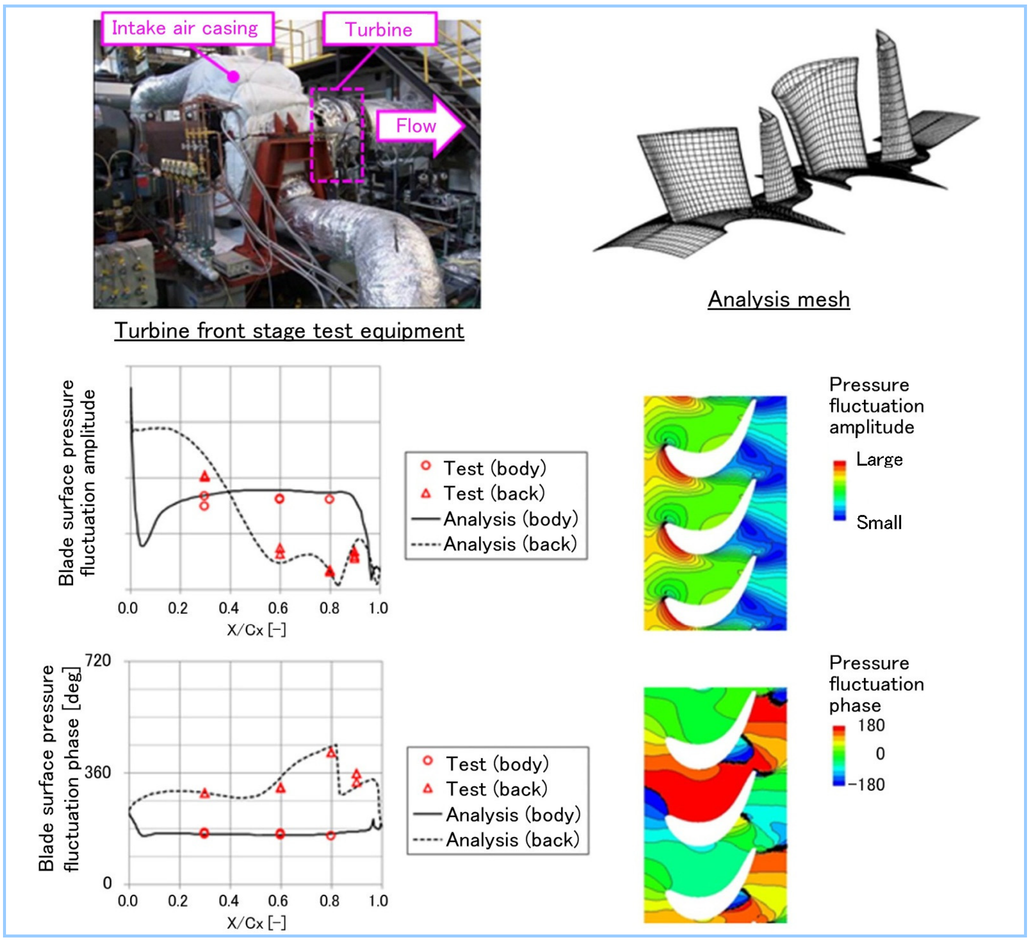

Figure 13 Improvement in prediction accuracy of blade row interference exciting force

2.7 Special measurement technology that supports development of gas turbines

In the actual equipment verification test at T-point, the appropriateness of the design of the developed element and its reliability was verified. High-temperature special measurement technologies are applied to the turbine first-stage rotor blade that is exposed to the most severe operation conditions, and these technologies are used to obtain valuable actual equipment data. Representative examples of such technologies include pyrometer, blade tip clearance and blade tip timing. The high-temperature pyrometer enables the verification of the film cooling effect by measuring the surface temperature of the turbine first-stage rotor blade. The high-temperature clearance technology measures the behavior of the clearance between the turbine first-stage rotor blade and the casing in unsteady transition and contributes to improvement in gas turbine performance. With the high-temperature blade tip timing technology that we developed, an evaluation of variation in the vibration characteristics of all of the turbine first-stage rotor blades under actual equipment conditions has approached the practical stage in recent years. These contribute to the vibration strength evaluation of the turbine first-stage rotor blade (**Figure 14**).

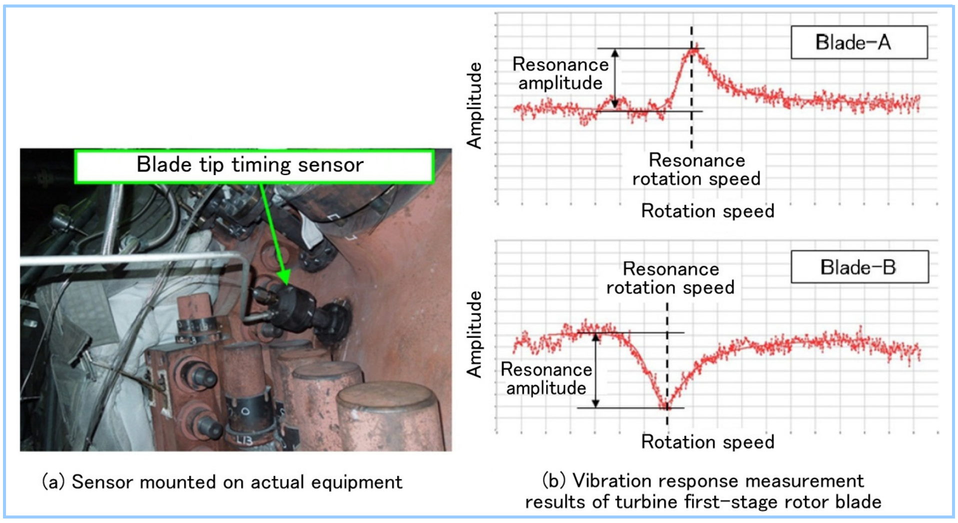

Figure 14 Actual equipment application example of high-temperature blade tip timing technology

2.8 Development of high-performance seal

At the high temperature of a 1700°C-class gas turbine, the thermal deformation of the components becomes significant, and in particular, the seals used in various parts in the cooling air system, which increases in importance when the temperature increases, are required to have followability to the transitional clearance change resulting from the thermal deformation. In the development of a high-performance seal, we are proceeding with an applicability evaluation of leaf seals that have such followability to the clearance change, as well as the seal performance and durability. A leaf seal has a flexible structure where thin plates are arranged in multiple layers in the circumferential direction so that it can follow the clearance deformation. The leaf seal ensures long-term seal performance, since it does not come into contact with the rotor using the dynamic pressure and pressure difference as the floating force. In this development, seal characteristic data of the clearance change was obtained using high-performance seal characteristic test equipment, and design guidelines for a leaf seal that has a higher followability and sealing performance against wider clearance changes were established (**Figure 15** and **Figure 16**).

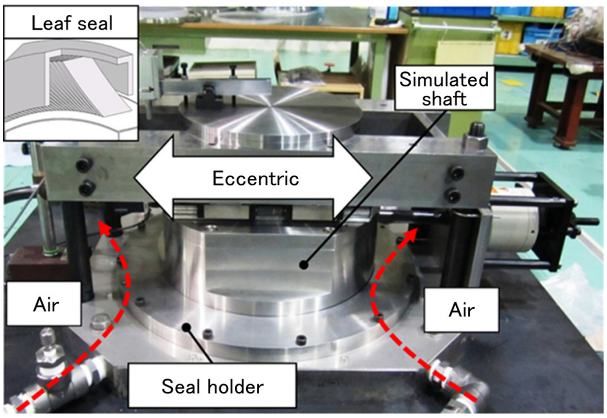

Figure 15 High-performance seal characteristic test equipment

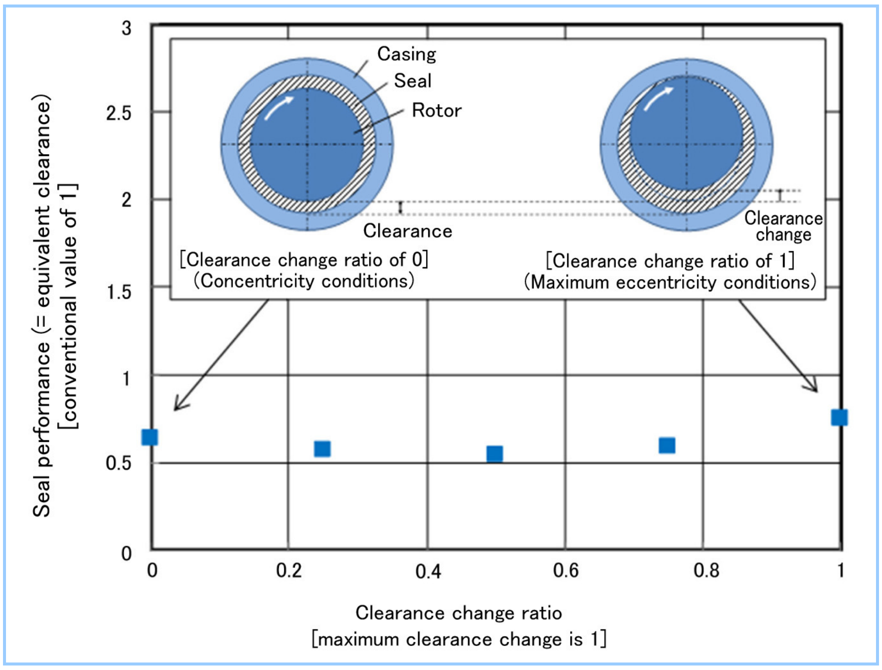

Figure 16 High performance seal characteristic test data (example)

3. Conclusion

The contents of this paper are part of research and development being conducted as the "1700°C-class gas turbine technological verification project" of the Ministry of Economy, Trade and Industry. For the technological development of a 1700°C-class gas turbine, technologies to be applied to actual equipment are being developed targeting the element technology development and verification required for practical application. Furthermore, some of the latest technologies, for which the effectiveness in terms of the improvement of performance and reliability has been verified through technical consideration and verification, have been applied to 1600°C-class J-type gas turbines. At the same time, we are working to enhance the reliability of the developed technologies by reflecting the obtained long-term operation data on the research. Through the diffusion of these combined power generation technologies, we hope to contribute to the reduction of CO_2 emissions form thermal power plants.

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