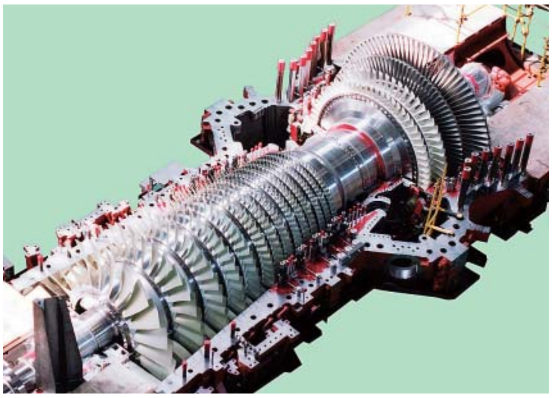

Operating Status of Uprating Gas Turbines and Future Trend of Gas Turbine Development

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Large frame gas turbines for power generation have been developed with more emphasis on improving their thermal efficiency based on the technology for raising to higher temperatures supported by such component technology as cooling and materials. Mitsubishi Heavy Industries, Ltd. (MHI) developed a 1,100 °C class D-type gas turbine in the 1980s and constructed the world's first successful large-scale combined cycle power plant. Since then, MHI has developed the F-type and G-type gas turbines with even higher turbine inlet temperature and has delivered many of them in Japan as well as overseas while accumulating successful commercial operations. MHI has constantly improved these gas turbines, adding to their successful operation. Now, MHI is participating in a national project to promote the development of component technology for the next generation 1,700°C class gas turbine, whose thermal efficiency will be improved significantly by raising the turbine inlet temperature.

1. Introduction

Large frame gas turbines fired by natural gas started playing an important role as the main facility in combined cycle power plants in the 1980s. Since then, their thermal efficiency has been continuously improved by raising the turbine inlet temperatures. Recently, as global environmental issues grow ever more serious, the Kyoto Protocol which came into force in February 2005 requires the Japanese government to comply with its CO_2 reduction quota. This in turn calls for power generation facilities with even higher efficiency.

In 1984, MHI developed the M701D gas turbine with a 1,100°C turbine inlet temperature and installed it in Unit No. 3, Higashi Niigata Thermal Power Station of the Tohoku Electric Power Co., which was the first large-scale combined cycle power plant in the world. Further to the successful operation of this gas turbine, MHI succeeded in developing the F-type and G-type gas turbines with even higher turbine inlet temperature as shown in **Fig. 1** while constantly accumulating successful operations in various large-scale thermal power plants. The resulting dramatic improvement in the combined cycle thermal efficiency shown in **Table 1** has significantly contributed to cutting down on energy consumption and pollution in the exhaust gases.

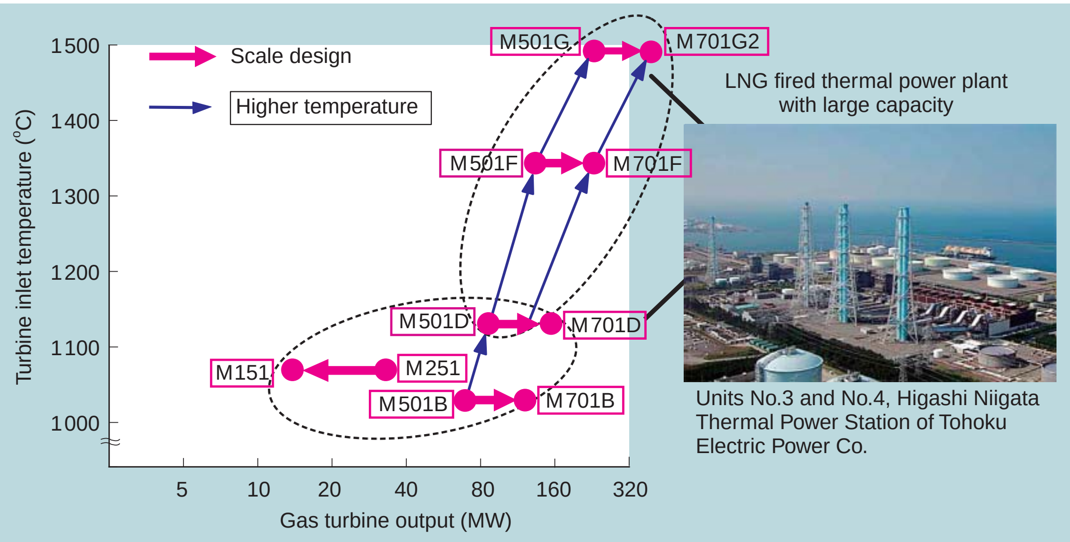

Fig. 1 History of MHI's large frame commercial gas turbines
MHI has improved the gas turbine performance by raising the turbine inlet temperatures while developing models from D-type, F-type to G-type.

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Table 1 Transition of MHI gas turbine performance

For 60 Hz utilities	M501D	M501F	M501G
The first operation year of prototype machine (year)	1980	1989	1997
Gas turbine power output (MW)	114	185	267
Gas turbine efficiency (% LHV)	34.9	37.0	39.1
Combined cycle efficiency (% LHV)	51.4	57.1	58.4
Pressure ratio	14	16	20
For 50 Hz utilities	**M701D**	**M701F**	**M701G2**
The first operation year of prototype machine (year)	1981	1992	2002
Gas turbine power output (MW)	144	278	334
Gas turbine efficienc (% LHV)	34.8	38.7	39.5
Combined cycle efficiency (% LHV)	51.4	59.0	59.3
Pressure ratio	14	17	21

Since then, MHI has been continuously improving the F-type and G-type gas turbines for better performance characteristics to meet the needs of a society concerned with global environmental issues. At the same time, to produce gas turbines of even higher thermal efficiency, MHI is participating in a national project to develop a 1,700°C class gas turbine doing research and development of the necessary component technologies.

This paper introduces the features of the improved technology applied to the advanced F-type and G-type gas turbines and operation results as well as the participation scheme and plans of the research and development of the component technologies for the 1,700°C class gas turbine, in the national project.

2. Technological features and operation results of advanced F-type and G-type gas turbines

To date, MHI's F-type and G-type gas turbines have accumulated about 3,800,000 hours and 500,000 successful operating hours, respectively. In the meantime, they have continuously been incorporated with the latest technology to achieve higher performance. The technological features and operation results of the improved items applied recently are as follows.

2.1 Technological features of advanced G series gas turbine

Figure 2 shows the advanced technological features that have recently been applied to the G-type gas turbines. After testing these technological features on an M501G gas turbine at MHI's long-term demonstration facility and verifying their performance and reliability[1], they were installed in the commercial, large frame gas turbines for power plants as shown in Fig. 2.

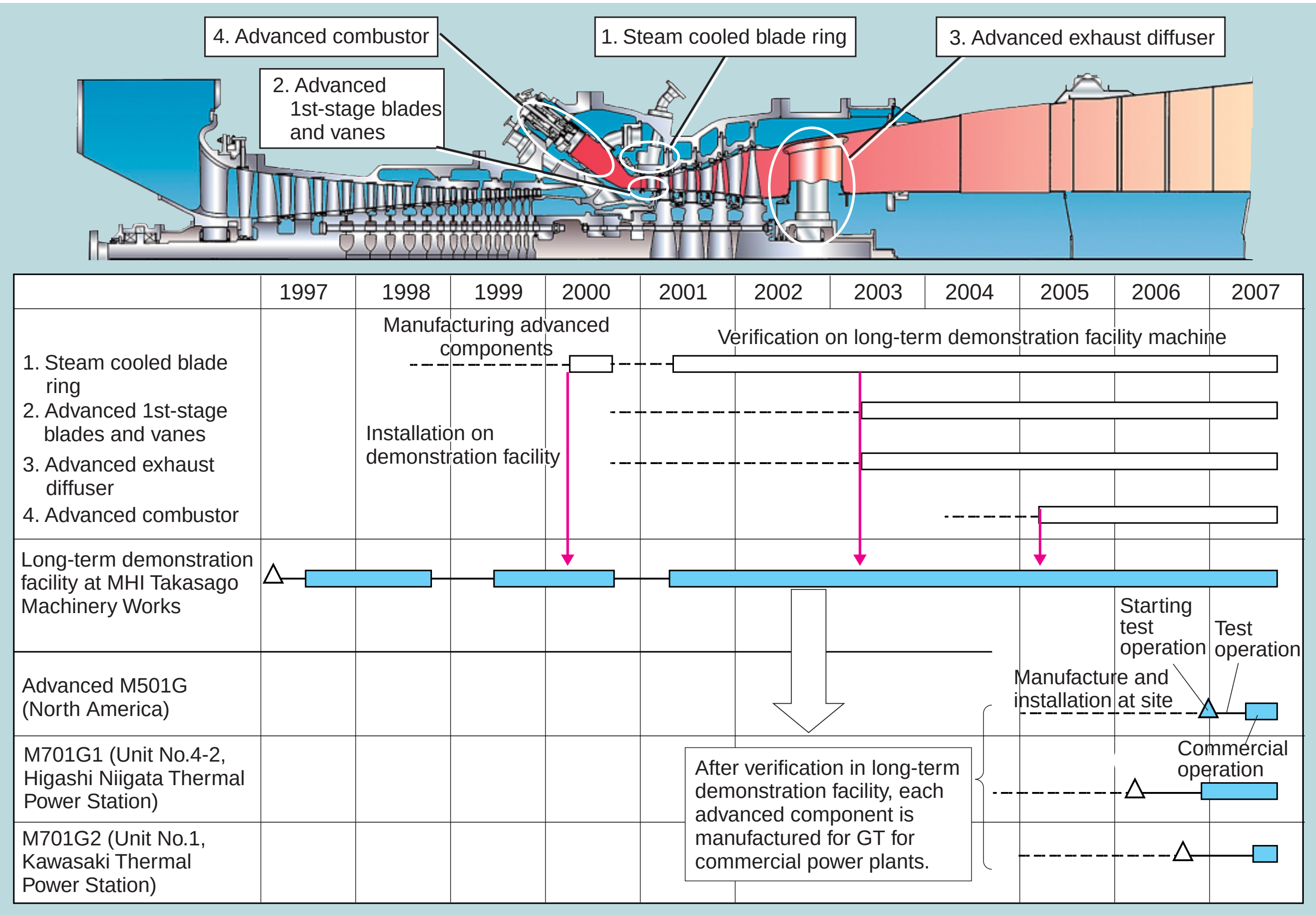

Fig. 2 Improved items and verification schedule
The improved items for type-G gas turbines are tested and verified at MHI's long-term demonstration facility M501G before installing them in commercial gas turbines.

(1) The stem cooled blade ring

The G-type gas turbine employs a steam cooling technique for the combustor. This positive utilization of steam has enabled the clearance control of the turbine blade chip. **Figure 3** shows the structure and system of M701G2 as an example. During start-up, steam running through the turbine blade ring cooling passages heats up the turbine blade ring to expand the tip clearances. When in loaded operation, steam cools down the blade ring to optimize the tip clearances. This system optimizes the clearances better during operation to improve the turbine performance than the previous one. A blade ring with this system was tested and verified on MHI's long-term demonstration facility M501G in 2000.

(2) Advanced turbine 1st-stage blade and vane

MHI has developed G-type advanced 1st-stage blades and vanes with improved aerodynamic and cooling technology. The materials are the same as previously where the 1st-stage vanes are made of MGA2400 and the 1st stage blades are made of MGA1400DS. The improved G-type advanced 1st-stage blades and vanes also employ the same design concepts where the 60 Hz and 50 Hz machines have the common basic dimensions such as the blade profile, blade height and chord length. These advanced blades were tested and verified on an M501G gas turbine at MHI's long-term demonstration facility in 2003.

(3) Advanced exhaust diffuser

The exhaust strut that supports the bearing is covered with a strut cover so that it is not exposed to high temperature exhaust gas. The profile of this cover was modified to a blade-like profile as shown in **Fig. 4**. This reduced aerodynamic losses while improving the turbine performance. The strut covers of blade profile were tested and verified on an M501G gas turbine at MHI's long-term demonstration facility in 2003.

(4) Advanced combustor

To deal with the ever more serious global environmental issues, MHI has developed an advanced combustor designed to further reduce NOx emissions while maintaining the combustion fluctuation characteristics and reliability. This advanced combustor was tested on an M501G gas turbine at MHI's long-term demonstration facility in 2005, and its performance and reliability were verified.

2.2 Advanced technology applied to F series gas turbines

Incorporating improvements in the cooling efficiency of high temperature components and applying higher strength materials and the latest seal technology enabled the turbine inlet temperature to be raised from 1,350°C to 1,400°C to achieve higher output and efficiency. These advanced F-type gas turbines are already in commercial operation on the market.[2] In order to achieve the higher performance, the rotor cooling air supply system (pre-swirl nozzles) previously introduced in the type-G gas turbines was installed on the more advanced F series gas turbine. The nozzle gives the cooling air supplied to the rotating disc by the same peripheral disc velocity to reduce the pumping losses when being introduced from the stationary component into the rotating component. This technology contributes to a performance improvement and has already been applied to aircraft engines. Before applying the pre-swirl technology to the more advanced gas turbines, the flow characteristics and pressure distributions were verified by component testing.[3]

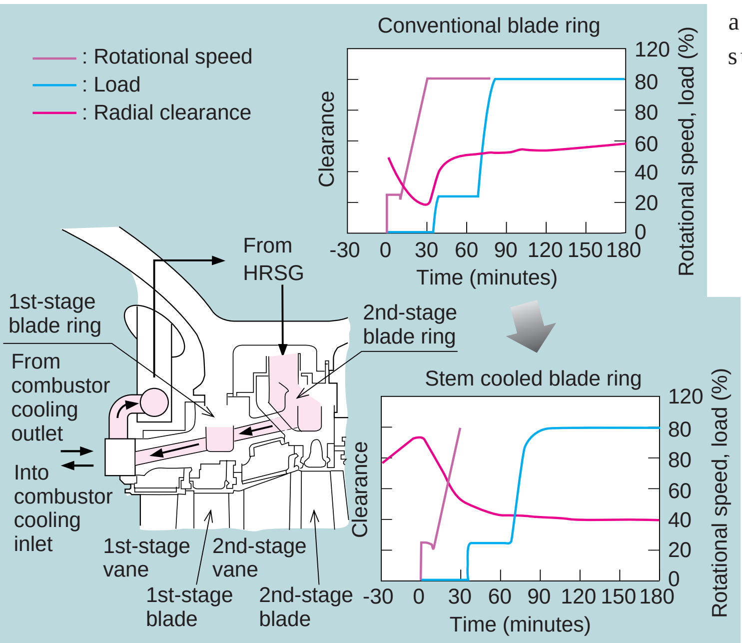

Fig. 3 System and structure of the stem cooled blade ring
By letting steam pass through, the clearance expands by warming during starting up while the clearance reduces more than that of the previous model by cooling under loaded operation to improve the turbine performance.

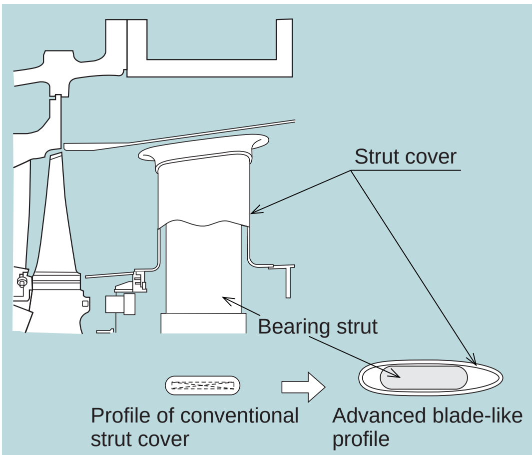

Fig. 4 Profile of advanced exhaust strut cover
Modifying the strut cover to the blade-like profile reduces the aerodynamic losses of the exhaust diffuser improving the performance.

Fig. 5 Unit No. 1, Kawasaki Thermal Power Station
The first machine of the M701G2 gas turbine is installed in Unit No. 1, Kawasaki Thermal Power Station of Tokyo Electric Power Co. After a successful test operation, it started commercial operation in June 2007.

2.3 Operation status of the advanced gas turbines

An advanced M701G1 gas turbine for 50 Hz utilities was installed in Unit No. 4-2, Higashi Niigata Thermal Power Station of the Tohoku Electric Power Co. Following the test operation started in April 2006, the power plant commenced commercial operation in December 2006. During the test operation, the features of the improved items like the stem cooled blade ring, advanced combustor and advanced turbine blades were specially measured. It was confirmed that they satisfied the criteria and verified reliability. In addition, incorporating the advanced combustor enabled stable combustion characteristics throughout the load ranges to be developed and proved to generate less NOx than the previous combustor for Unit No. 4-1.

The M701G2 gas turbines were installed in Unit No. 1, Kawasaki Thermal Power Station of Tokyo Electric Power Co. (single-shaft type combined cycle power plant x 3) as shown in **Fig. 5**. The third shaft, being the first machine, started test operation in October 2006. After reaching the rated output of 500 MW and confirming its compliance with the guaranteed performance in January 2007, the machine started commercial operation in June 2007. During the test operation, various confirmation measurements took place on such improved items as the stem cooled blade ring, advanced combustor and advanced turbine blades. The results were as intended.

After being thoroughly verified on MHI's long term demonstration facility, the first advanced M501G gas turbine for 60 Hz utilities was delivered to Port Westward in Oregon, USA, for commercial operation. The test operation commenced in January 2007 and thoroughly verified compliance with the guaranteed performance, NOx emissions and other specifications. The power plant started commercial operation in June 2007.

An advanced F-type gas turbine was installed in Castelnau in the central part of Spain. It started test operation in January 2006 and commercial operation in August 2006. Special measurements of the pre-swirl nozzle were also made at this site. The resulting pressures, temperature distributions and cooling air flow verified the performance and reliability.

During the test operations, it was confirmed that both advanced gas turbines demonstrated better performance and reliability than those of the previous models. The machines have been operating very well while enjoying high customer valuation and satisfaction.

3. Current status of component research and development for 1,700°C class gas turbines

As global warming is becoming a serious issue, there have been increasing calls for reductions in CO_2 emissions. Since power generation plants are responsible for one third of CO_2 emissions, a significant improvement in efficiency of power generation plants would be effective in reducing CO_2 emissions. For example, replacing 1,250,000 kW coal-fired power plants with combined cycle power plants with 1,700°C class gas turbines would reduce the total CO_2 emissions in Japan by 0.4%. This is because a gas turbine with the turbine inlet temperature of 1,700°C achieves a thermal efficiency of 62 to 65% as shown in **Fig. 6**.

To contribute to reducing global warming by making the current gas turbines operate at higher temperature and efficiency, MHI is participating a national project to develop a 1,700°C gas turbine.[4] The project aims to develop in four years the component technology of combustor, coating, turbine blades, compressor and heat resistant materials, which are essential to a 1,700°C gas turbine. The next section of this paper outlines some of our major achievements.

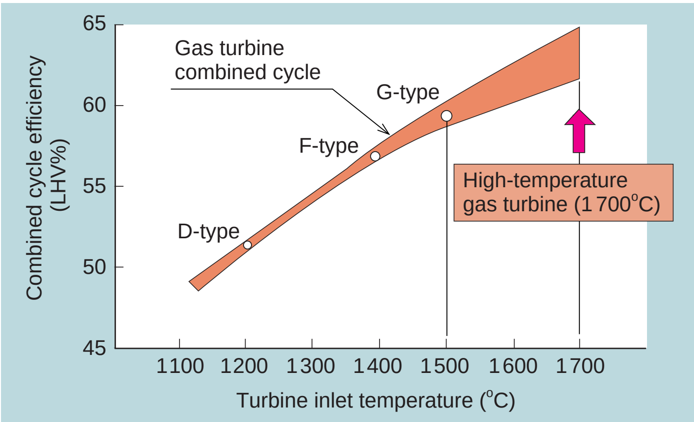

Fig. 6 Combined cycle thermal efficiency VS. Turbine inlet temperature
With the turbine inlet temperature rising as models develop from D-type, F-type to G-type, the combined cycle efficiency has improved. The 1700°C class machine will achieve the thermal efficiency of 62% to 65%.

3.1 Combustor

A 1,700°C class gas turbine requires an exhaust gas re-circulation system and a new concept combustor to reduce NOx emissions. The new combustor enables low NOx combustion over the entire load range by burning in premixed combustion mode with a partial load and in diffusion combustion (rich and lean combustion) mode with the rated load. MHI designed and prototyped the new concept combustor and conducted an atmospheric-pressure, 1,700°C combustion test. The test employed air with a low oxygen concentration to simulate the exhaust gas re-circulation. **Figure 7** shows the results of the atmospheric-combustion test. The NOx emission converted to the value under pressure was less than the target NOx emission of 50 ppm, confirming the possibility of realizing a 1,700°C class combustor that combines the new concept combustor with the exhaust gas re-circulation system.

3.2 Turbine

Turbine cooling technology, thermal barrier coating and heat resistant material technology are indispensable in developing the 1,700°C class gas turbine. The national project is developing such technologies as high performance film cooling, thermal barrier coating with a low thermal conductivity coefficient and alloys with excellent oxidation resistance, high temperature creep strengths and thermal fatigue strengths while maintaining good casting performance. The following is a partial list of present achievements.

Figure 8 shows the latest results of measuring the coefficient of thermal conductivity of the thermal barrier coating. It was confirmed that the coefficient of the thermal conductivity of the newly developed thermal barrier is lower by approximately 20% than that of the conventional YSZ (partially yttria stabilized zirconia).

The aerodynamic design conditions of the 1,700°C class gas turbine are a pressure ratio and aerodynamic load factor 1.5 times or more and 1.3 times the previous designs, respectively. Since the previous technology would have caused the efficiency to be lower, a new concept blade was developed. A three-dimensional end wall concept suitable for a high-load blade was established. The subsequent high-temperature cascade test confirmed a reduction in the aerodynamic losses (**Fig. 9**).

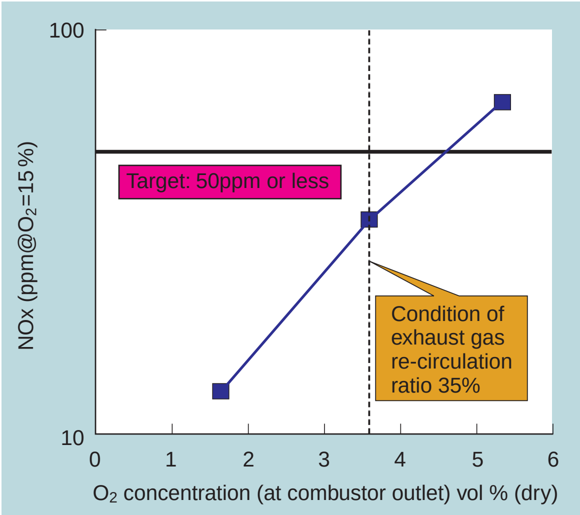

Fig. 7 Results of atmospheric-pressure combustion test of new concept combustor
A new concept combustor incorporating premixed combustion and diffusion combustion was designed. The prototype took an atmospheric-pressure combustion test. The test results confirm the possibility of realizing NOx emissions of 50 ppm or less under the exhaust gas re-circulation system.

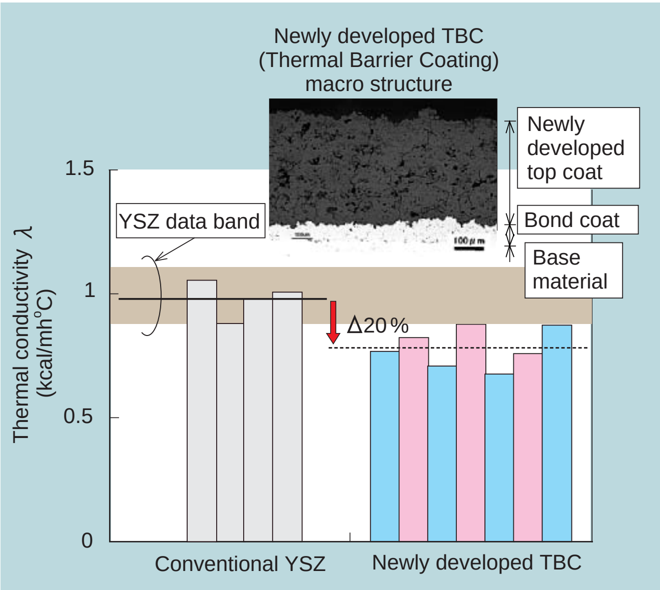

Fig. 8 Results of measuring coefficient of thermal conductivity of newly developed thermal barrier coating
The thermal barrier coating being developed for a 1 700°C class gas turbine proves through a component test that it produces a thermal conductivity 20% lower than that of the previous one.

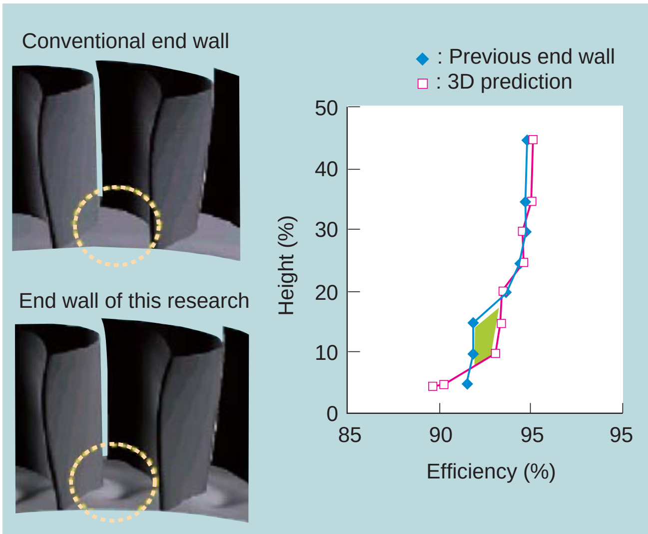

Fig. 9 Profile and effect of three-dimensional end wall
The high-temperature cascade test confirmed the effectiveness of the advanced three-dimensional end wall that reduces the secondary flow losses under higher aerodynamic load conditions than the previous one.

3.3 Compressor

Under the high pressure conditions of the 1,700°C class gas turbine, it is necessary to develop a compressor that produces a better efficiency than that of the existing design with the pressure ratio of 25 while minimizing the number of steps. Based on the concept of secondary flow vortex control by a new three-dimensional profile and a reduction in friction losses due to load distribution control, a subsonic cascade was designed with its effectiveness confirmed by a high-temperature cascade test. As shown in Fig. 10, the measured efficiency was good, being approximately 1% higher than that of the CFD prediction.

4. Conclusion and future trend of gas turbine development

From the viewpoint of energy conservation and low pollution, higher efficiency and performance continue to be important issues for gas turbines development. MHI continuously improved the F-type and G-type gas turbines based on a sure-footed verification system testing and verifying the advanced modifications on MHI's long-term demonstration facility M501G before installing them on commercial gas turbines. In recent years, since the combined plants equipped with these advanced gas turbines have steadily accumulated good operation records in Japan as well as overseas, they are considered to have provided society with environment-friendly energy sources.

In addition, by participating in the national project of developing a 1,700°C class high-temperature gas turbine, MHI has researched and developed component technology while securing concrete achievements to promote significant efficiency improvements in the future.

Since these component technologies are considered to be applicable to existing F-type and G-type machines, MHI is also planning to study how to apply them and improve the performance of the existing F-type and G-type machines so as to offer more environment-friendly energy sources. While the research and development of the 1,700°C class gas turbine continues, a verification test at the full-scale machine level is indispensable before commercial application of these technologies. To achieve this goal, the united cooperation of the government, utility companies and machine manufacturers will be necessary.

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