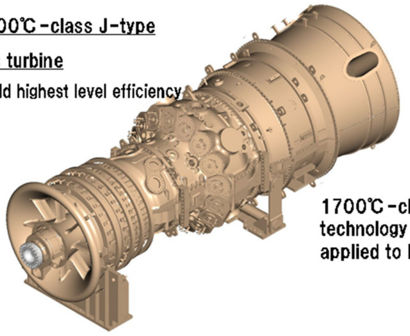
Development of Key Technology for Ultra-high-temperature Gas Turbines



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Gas turbine combined-cycle power generation is expected to lead to a long-term extension of the gas turbine market by providing the world's cleanest and most economical thermal power plants with fossil fuel coexisting with natural energy and nuclear power generation. The technology required for a 1,700°C-class gas turbine is being developed as part of a national project to pursue higher efficiency. State-of-the-art technologies, whose contributions toward improved efficiency have been verified, have already been applied to the development of the world's first 1,600°C-class J gas turbine. This paper describes the current status of state-of-the-art gas turbine technology aiming for its practical implementation.

1. Introduction

Gas turbine combined-cycle (GTCC) power generation contributes toward reducing fuel consumption and emissions as it can be used to build the cleanest power plants that consume fossil fuels. From a social and economic standpoint, GTCC power generation is expected to meet the following needs:

(1) A growing long-term world market has been forecast for GTCC power generation.

(2) In developing countries, a great demand exists for GTCC power generation, which can be produced after a short construction period and provide a stable supply of electricity to develop electric infrastructure.

(3) In developed countries, a need exists for highly efficient power generation to enhance economic efficiency and environmental adaptation.

(4) It is increasingly important to seek the superior load-absorbing capability of GTCC power generation from the viewpoint of combining it with natural energy and nuclear power generation.

Mitsubishi Heavy Industries (MHI), Ltd., is committed to pursuing the technological development of a 1,700°C-class gas turbine as part of a national project. This paper describes the technologies applied to newly developed 1,600°C-class J gas turbine and discusses how they may be used for the 1,700°C-class gas turbine project.

2. Component Technology of Ultra-high-temperature Gas Turbines

In response to the needs of society described above, the development of component technology for a 1,700°C-class gas turbine has progressed in Japan as part of a national project. **Figure 1** shows the component technology items under development.

2.1 Component technology to support low NOx combustor development

Because NOx concentration increases exponentially with combustion temperature, it is essential to develop NOx-reduction technology for a 1,700°C-class gas turbine. Therefore, the introduction of an exhaust gas recirculation (EGR) system was studied. In the 1,600°C-class J gas turbine, the non-EGR combustor which is adopted to G-type gas turbine was selected.

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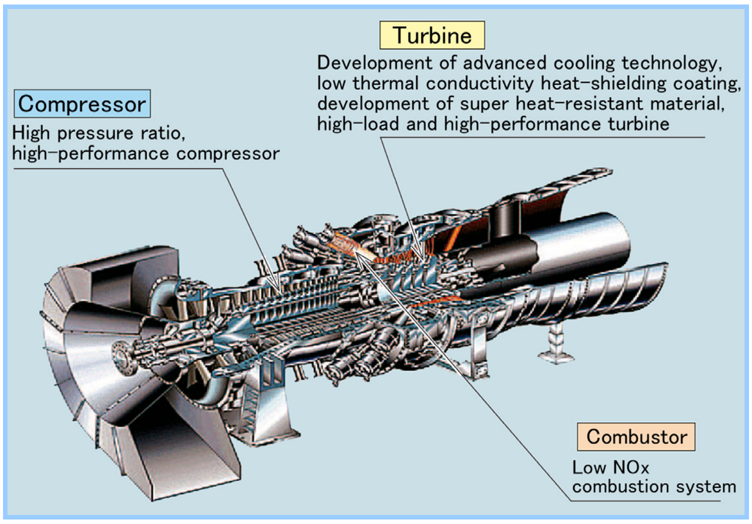


Figure 1 Development of advanced technology for a 1,700°C-class gas turbine

We now describe the measuring technique used to determine the unsteady NOx concentration distribution, which is used to support combustor designs. **Figure 2** shows measurements of the cross-sectional fuel concentration distributions of a new-concept combustor by means of laser-induced fluorescence spectroscopy (PLIF) corrected for the combustion temperature. Highly homogenized spatial distributions were observed. However, homogenized temporal concentrations are also crucial to achieve NOx reduction in an ultra-high-temperature gas turbine. Accordingly, high-accuracy unsteady combustion analysis technology was developed using large-eddy simulation (LES) technique as well as unsteady concentration-distribution measuring techniques. **Figure 3** compares the concentration analyses and measured values for both of instantaneous and averaged distribution. These are also the basic technologies that support the 1,600°C-class J combustor development.

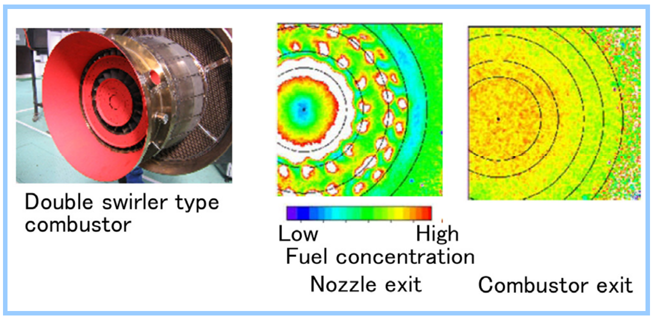
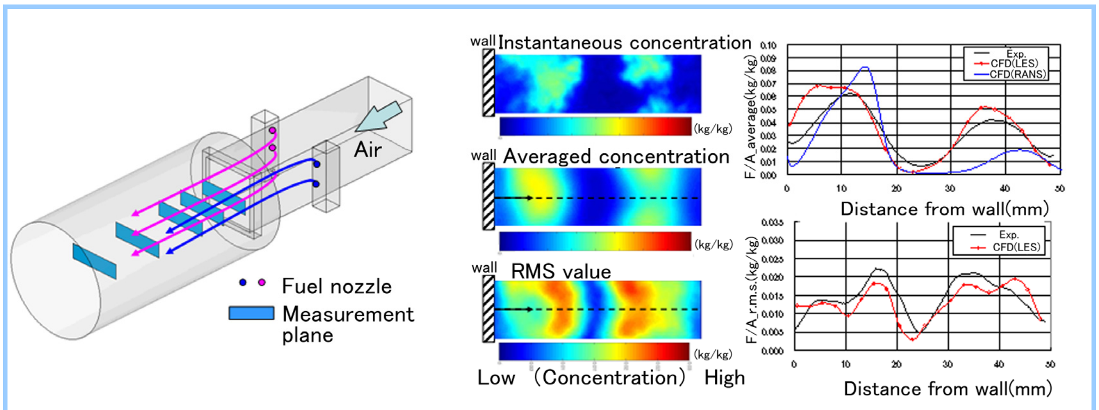


Figure 2 Time-averaged measurements of the cross-sectional combustion concentration distribution of a new-concept combustor by means of PLIF



(a) Unsteady PLIF instrumentation system and schematic diagram of the measurement instrument

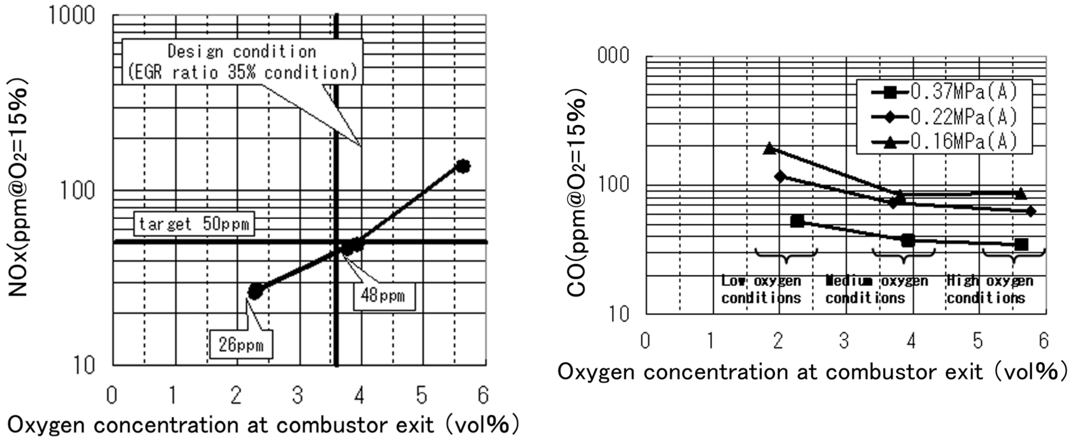
(b) Time averaged PLIF measurement results

(c) Comparisons of Reynolds-averaged Navier-Stokes (RANS) computational fluid dynamic analyses and large-eddy simulation (LES)

Figure 3 Unsteady PLIF measurements and CFD analysis results

The measuring technology for unsteady concentration distributions as well as highly accurate unsteady combustion flow analysis technology was developed by means of LES. Instantaneous values of the concentration distribution are substantially different from averaged values. Predictability improvements using LES were demonstrated.

In the 1,700°C-class combustor, which adopted an EGR system, the measured NOx and CO emissions showed that the NOx was below 50 ppm and the CO was around 10 ppm, as indicated in **Figure 4**. This suggests that the technology is feasible for future gas turbine development.



(a) Measured NOx (b) Measured CO

Figure 4 Measurements of NOx and CO at the combustor outlet
The measured NOx and CO emissions of a 1,700°C-class combustor by use of EGR demonstrated that the NOx was below 50 ppm and the CO was around 10 ppm.

2.2 Advanced cooling technology

The blade and vane of an ultra-high-temperature gas turbine are exposed to very high thermal loads and stresses. To ensure component reliability without sacrificing cycle performance, we must retain a high cooling efficiency using the minimum amount of film cooling air. Furthermore, a hot spot caused by inadequate distribution of the cooling air on the surface of the turbine blade may become a fatal defect. Therefore, we examined the film-cooling efficiency in a rotational system.

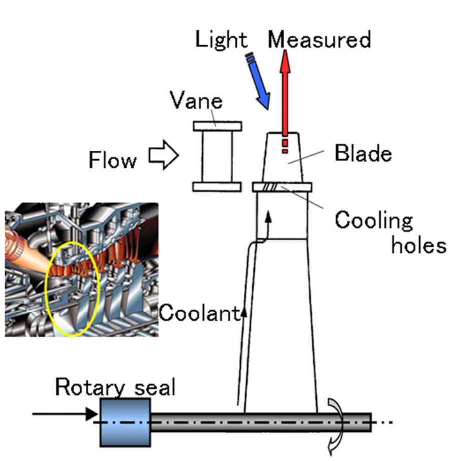
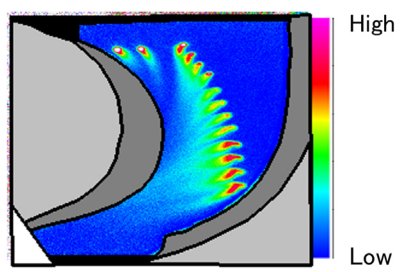
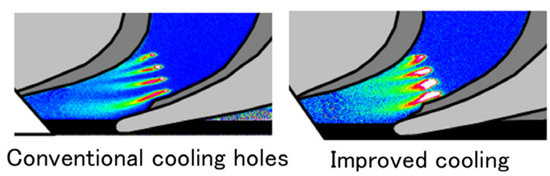


Figure 5 Conceptual diagram of the rotational test rig simulating the enclosed portion of an actual turbine
The film cooling efficiency on the blade surface and the platform surface was measured under the influence of three-dimensional blade–vane interaction.



(a) Film cooling efficiency on the blade platform



(b) Film cooling efficiency measured near trailing edge (left: conventional, right: improved film cooling holes)

Figure 6 Film cooling efficiency on the blade platform surface
The measurements on the first-stage blade shown in Figure 5 were obtained using pressure-sensitive paint.

Figure 5 shows a conceptual diagram of our rotational test device. The film-cooling efficiency on the blade surface and the platform surface was measured under the influence of three-dimensional blade–vane interactions, wherein the aerodynamic similarity condition was based on simulating the velocity triangle in an actual turbine. The measurements were compared with the film cooling efficiency measured on a stationary flat plate. The measurements were conducted using pressure-sensitive coating material. High-temperature gas and cooling air in the actual turbine were simulated by air in the main flow and by nitrogen gas from the secondary air system, respectively, of the rotating rig illustrated in Figure 5. The distributions of oxygen concentration on the surface due to the nitrogen ejected from the film cooling holes were measured by means of image processing.

Figure 6(a) shows measurements of the film cooling efficiency distributions on a blade platform surface. Each distribution varied significantly depending on the film cooling port, and this was thought to be affected by the passage vortexes of a cascade and by unsteady effects caused by the blade and vane interactions. **Figure 6(b)** compares the film cooling efficiency distribution between a conventional film cooling geometry and a highly efficient film with an optimal port shape on the same rotating blade, with the film port located near the trailing edge. The results confirmed that more homogeneous and better film cooling efficiency was obtained for the latter case. This high-efficiency cooling technology was applied to the design of the 1,600°C-class J gas turbine.

2.3 Advanced thermal barrier coating

For an ultra-high-temperature gas turbine, the thermal barrier coating (TBC) on the turbine blade is critical. Because the gas temperature rises in the vicinity of the blade, a material exploration system that uses first-principle calculations to determine the material properties at an atomic level was used to develop compounds that are durable and have a low thermal conductivity. Complex compound ceramics have a higher thermal barrier effect than yttria-partially-stabilized zirconia (YSZ) (consisting of ZrO_2 partially stabilized using 8 wt% Y_2O_3) in current use by approximately 20%. Another important property is durability at high temperatures, in particular, phase stability for a long term operation. This was measured under high temperatures for 1000 h. The test results are shown in **Figure 7**. The heating condition was a top coat surface temperature of 1,200–1,400°C, which corresponds to an actual condition of 1,700°C in the gas turbine. As shown in the figure, the developed ceramic materials had much more stable high-temperature properties than YSZ.

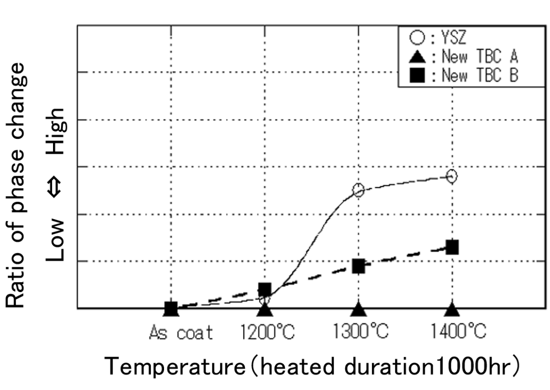


Figure 7 Property variations of an advanced TBC at ultra-high temperatures (proportion of phase change)

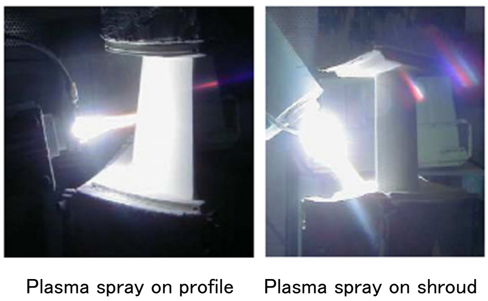
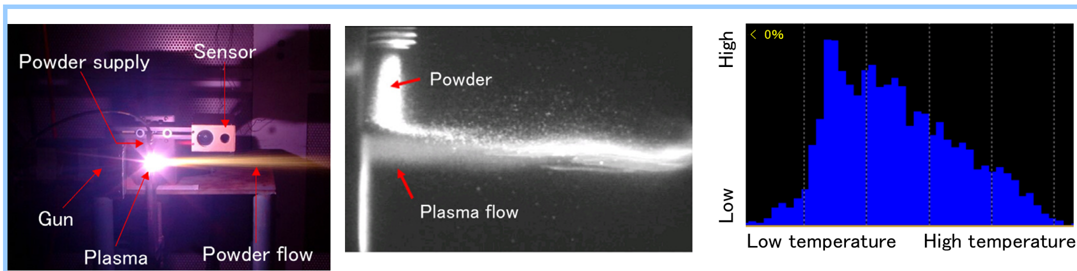


Figure 9 Advanced TBC sprayed on a 1,500°C-class first-stage vane



(a) Measuring the phase of plasma spraying for an advanced TBC

(b) Diffusion of particles inside the plasma when the powder is injected into the plasma

(c) Measurements of the powder temperature in the plasma (probability distribution)

Figure 8 Plasma spray condition for the advanced TBC

Further material development and optimization of the plasma spray conditions are required to put the advanced thermal barrier coating into practical use. Figure 8 shows the coating powder supplied into high-temperature plasma. The photograph, taken with an ultra-high-speed camera, shows the diffusion state inside the plasma when the powder is injected into a plasma flow at a temperature of more than two thousand degrees Celsius. Measurements of the powder–temperature dispersion in the plasma are also shown in **Figure 8**. Studies on the correlation of operating conditions with thermal fatigue life and thermal conductivity have facilitated the development of optimal spraying conditions. **Figure 9** shows the candidate material as it is sprayed on the first-stage vane of the M501G 1,500°C-class gas turbine. The vane was installed on a verification power plant in the MHI Takasago Machinery Works, and its durability was tested under actual operating conditions at 1,500°C.

2.4 Aerodynamic technology supporting high-temperature high-performance designs

Because a high-temperature gas turbine applies steam cooling to the combustor transition piece, the side wall of the transition piece outlet must be thick. The temperature of the first-stage vane is usually designed to be a multiple of the combustors, with due consideration for the periodicity of the inlet gas temperature distribution. In such a case, the turbine efficiency is optimized by arranging the relative circumferential position of the downstream row-1 vane relative to the side wall of the combustor outlet. **Figure 10** shows predictions of the combustion gas flow by means of computational fluid dynamics (CFD) and verification results of the performance improvement by high-speed rotating cascade tests.

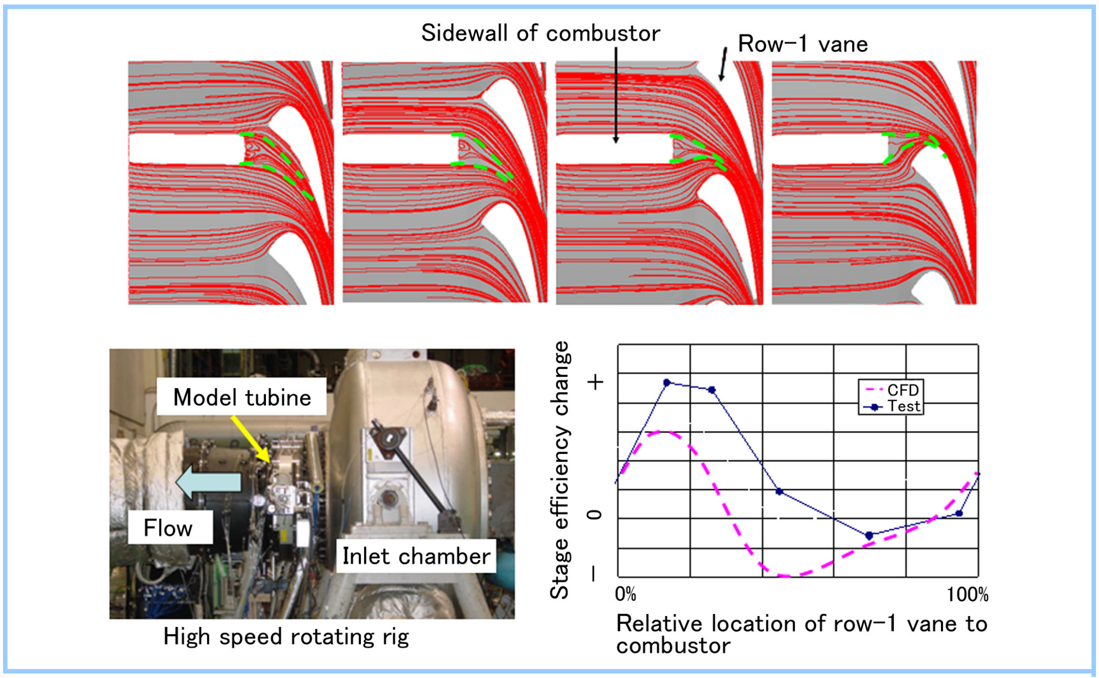


Figure 10 Optimization of the turbine efficiency with consideration for the combustor

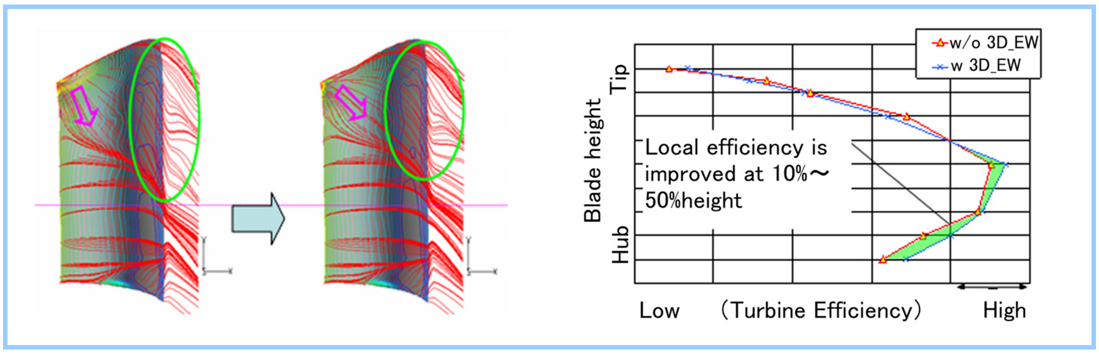


Figure 11 New three-dimensional design and verification of the performance improvement by rotating cascade tests

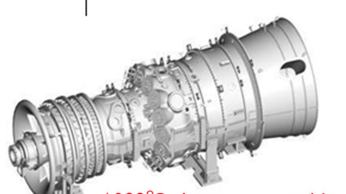
Reducing the secondary flow of the tip side in the suction surface of the downstream vane improves the flow at 10–50% at vane height (left: streamlines obtained using CFD, right: efficiency distribution in the spanwise direction).

The performance of the downstream vane is reduced by the increased tip-clearance flow from a freestanding blade because of the higher aerodynamic load. To mitigate this performance loss, a new-concept three-dimensional aerodynamic design technology that reduces the secondary flow of the downstream vane was developed by combining the three-dimensional blade shape with the three-dimensional end wall. **Figure 11** shows predictions of the improved effect on the flow field using CFD and verification of the performance improvement by rotation cascade tests.

2.5 Development roadmap for a 1,700°C-class gas turbine and development of a 1,600°C-class J gas turbine

Table 1 shows a roadmap for developing 1,600°C- and 1,700°C-class turbines up to practical implementation. The first step of a 4-year plan, which started in 2004, to develop the component technology for a 1,700°C-class gas turbine has been completed, and we are currently working on the second step. After the component technology has been developed, we will start working on developing the design for a 1,700°C-class demonstration gas turbine. The world's first 1,600°C-class J type has already been developed by compiling the proven component technologies for 1,400°C-class F and 1,500°C-class G and H turbines, as well as by introducing the above technology that could be applied to practical use. In the new 1,600°C-class J gas turbine, the GTCC power generation efficiency surpasses 60% (low heating value basis), so that the world's highest level of power generation efficiency can be attained.

Table 1 Development roadmap of a 1,700°C-class gas turbine and technology application to a 1,600°C-class J gas turbine

	2000	2005	2010	2015～
Advanced technology development ○1500℃→1700℃ ○Efficiency 53%→56%(→8%) (HHV) ○CO_2(kg-CO_2/kwh) 0.34→0.31～0.32		Step-1 ('04～'07) Step-2 ('08～'11)		
Application to gas turbines ○Efficiency +2% ○Application to 1600℃-class GT		Verification with 1500℃-class GT Development of World first 1600℃-class GT		 1600℃ J-type gas turbine
1700℃-class gas turbine development			Design	Verification test 1700℃GTCC
Application to IGCC				1700℃ IGCC

2.6 CO_2 reduction by state-of-the-art complex power generation

If a 1,700°C-class gas turbine is realized to practical use as the main turbine of GTCC power generation facilities, the power generation efficiency will surpass 62% (low heating value basis), achieving extensive improvements compared with conventional thermal power generation. For example, assuming that the thermal efficiency of 1.25-MW coal-fired thermal power generation facilities is 44% (low heating value basis), the CO_2 emissions per year are 8.53 megatons. If the coal-fired thermal power plant is replaced with natural gas-fired 1,700°C-class J GTCC power generation facilities, the CO_2 emissions per year will be 3.24 megatons, or a 62% reduction. Since this reduction is 0.4% of the total CO_2 emissions of 1.34 billion tons in 2006 in Japan, this is a very large number that will have a large influence in the country, which has a high CO_2 reduction target. In addition, considering that the CO_2 emissions of Japan are only slightly less than 5% of the total world emissions, extension of state-of-the-art GTCC power generation technology to the world has the potential to make a large contribution toward solving global environmental problems.

3. Conclusion

The technology development for a 1,700°C-class gas turbine is underway, building on the technology developed from 2004 to 2007, and aims to reach the stage of practical application during a 4-year project extending from 2008 to 2011. The project has progressed with the collaboration of academics, industry, and government, in cooperation with the Ministry of Economy, Trade and Industry and the Ministry of Education, Culture, Sports, Science and Technology. The initial technology development consisted of basic elementary tests in a laboratory. Many new technologies have been introduced in the project. At present, module tests simulating closer actual operation conditions and verification tests using actual 1,500°C-class G gas turbines are progressing. The content of this paper is part of the research and development activities underway as part of the “advanced technology development project for efficient energy application” encouraged by the Ministry of Economy, Trade and Industry. Through technological study and verification, state-of-the-art technologies that have proved useful for performance and reliability improvements were immediately applied to the design of the 1,600°C-class J gas turbine. We believe that we can contribute to reduced CO_2 emissions by spreading our state-of-the-art combined cycle power generation technology throughout the world.