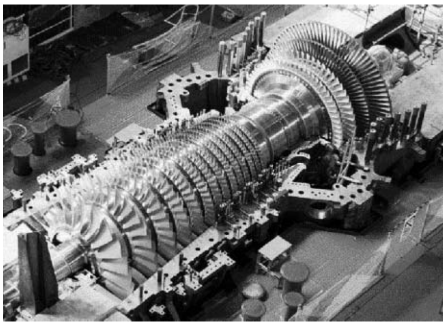

Latest Technology for Large-Capacity Gas Turbine

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In developing large-capacity gas turbine for use in power generation as the main machines in combined cycle power plants, Mitsubishi Heavy Industries, Ltd. (MHI) has made every effort to increase thermal efficiency. However, the global environment is growing into a serious problem day by day, as evidenced by frequent news reports of unusual weather attributable to global warming. Under such conditions, Japan is certainly required to achieve the goal of reducing the emission of greenhouse gases such as CO_2, under the Kyoto Protocol that came into effect in February this year. Against this background, a national project to develop the component technologies for a 1700°C class high efficiency gas turbine was started in fiscal year 2004 with schedule to complete in four years. MHI participates in this project and has started the development work allocated to them. When the 1700°C class gas Turbine is commercialized, it will become possible to reduce the overall emission of CO_2 in Japan by 0.4 %, if all the 1.25 million kW coal-firing power stations operating in Japan are replaced by combined cycle power plants equipped with the 1700°C class gas Turbine. This reduction effect is quite significant when compared to the 6 % reduction targeted by the Kyoto Protocol. Accordingly, this effect brought by the development of the 1700°C class high efficiency gas Turbine will spread not only to Japan but also to the world, so that it is expected to contribute to an improvement in the global environment. This paper introduces the results and future plan of development project for component technologies of this gas turbine.

1. Introduction

Large-capacity gas turbines for use in power generation with natural gas firing have positively been used as the main machine in thermal power stations since the early 1980s. After that the use of such turbines has contributed significantly to the reduction of energy consumption and exhaust gas pollution. MHI has commercialized 1 500°C class gas turbines (M501G and M701G) and received thirty-six orders for these turbine sets. The eighteen sets have already been operating commercially in sound condition.

From the viewpoint of protecting against global warming, Japan is certainly required to reduce CO_2 emissions to 6 % of less than 1990 levels, between 2008 and 2012, in accordance with international exhaust gas restriction set forth in the Kyoto Protocol, which came into effect in February 2005. In order to further improve the efficiency of present gas turbines used for combined cycle power plants and contribute to efforts to prevent global warming, MHI has participated in a national project to develop the component technologies for t he 1700°C class gas Turbine. This paper describes the results of the various investigations performed in this project and briefly considers future plans of the project.

2. Increase of cycle temperature and its contribution to the environment

When the maximum temperature of a thermal cycle is raised, the efficiency of recovery energy conversion is increased. **Fig. 1** shows the relationship between the turbine inlet temperature and combined thermal efficiency (LHV). The combined cycle thermal efficiency of t he 1 700°C class gas Turbine, which inlet temperature is further increased over that of present gas turbines (1 400°C in the F series and 1 500°C in the G series), increases from 62 to 65 % (LHV).

On the other hand, the contribution of the increase in the combined cycle thermal efficiency to the environment is measured by the reduction in the amount of CO_2 emissions released each year. The amount of CO_2 exhausted from the current conventional coal-fired thermal power plant which capacity is 1.25 million kW and 44% of thermal efficiency is estimated to be approximately 8.53 million tons per year. Then in case the combined cycle plant with the 1700°C class gas Turbine is substituted for the conventional thermal power plant, the amount of CO_2 is estimated to be approximately 3.24 million tons per year. This means that a 62% reduction in the amount of CO_2 released into the atmosphere can be expected. This reduction effect corresponds to about 0.4 % of the 1336 million tons that is the total emission of CO_2 during fiscal 2003 in Japan.

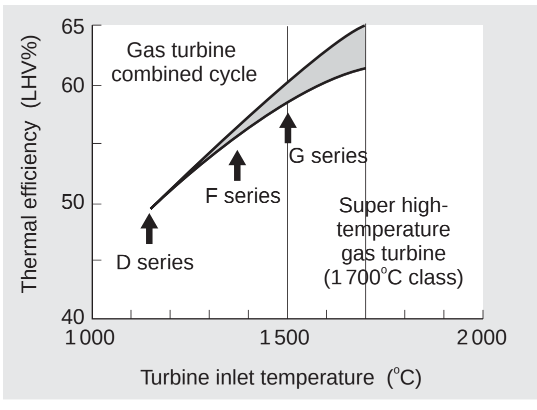

Fig. 1 Relationship between turbine inlet temperature and combined efficiency

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3. Development of component technologies for the 1 700°C class gas Turbine

The purpose of the national project is to develop the component technologies such as the coatings, cooling technology for blades and vanes, combustors, turbines, compressors, and heat-resistant materials that are fundamental issue for the 1 700°C class gas Turbine within four years. Among these technologies, the coating, cooling technology for blades and vanes, combustor, turbine, compressor are to be developed as part of a project supported by the Agency for Natural Resources and Energy of the Ministry of Economy, Trade and Industry (METI), while the super heat-resistant materials are to be developed as part of a research project entrusted by the New Century Heat-resistant Material Project, in cooperation with the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the National Institute for Materials Science (NIMS), which is an independent administrative agency.

3.1 Exhaust Gas Recirculation Combustion System

(1) Investigation of Cycle

The cycle calculation for the framework of the overall system was carried out. In developing the 1 700°C class gas Turbine, it was essential to introduce an exhaust gas recirculation system, from the perspective of preventing NOx emissions. In studying the exhaust gas recirculation system, there are two choices, as shown in **Fig. 2**. One method consists of introducing the exhaust gas from the heat recovery boiler into the upstream side of the compressor (System A), while the other method consists of compressing the exhaust gas up to the casing pressure of the gas turbine using a separate compressor, and mixing it with fuel gas, then introducing into the combustor to be burned (System B). The results of the cycle investigation showed that System B required a separate compressor and gear unit, and further, that system efficiency is 0.7 % lower than that for System A, due to the difference of the compressor efficiency. In order to determine the turbine inlet pressure, the optimum pressure ratio was defined by investigating the effect of the inlet pressure on combined efficiency, using pressure ratio as a parameter. Further detailed simulations and study will be performed to improve the accuracy of the result.

(2) Investigation of exhaust gas recirculation combustor

There are two choices for a combustor applicable to the 1 700°C class gas Turbine. The one is the premixed type combustor, which is the most common type used at present for a low NOx combustor, and the other is the diffusion type combustor, in which fuel is mixed and reacted with air. The merits and demerits of both types of systems were investigated, based on trial designs for both basic formations. **Fig. 3** shows the trial designed configuration of the diffusion type combustor as an example. Computational fluid dynamics (CFD) was carried out respectively for both types of combustor, in order to estimate the temperature distribution and NOx concentration distribution of each (**Fig. 4**).

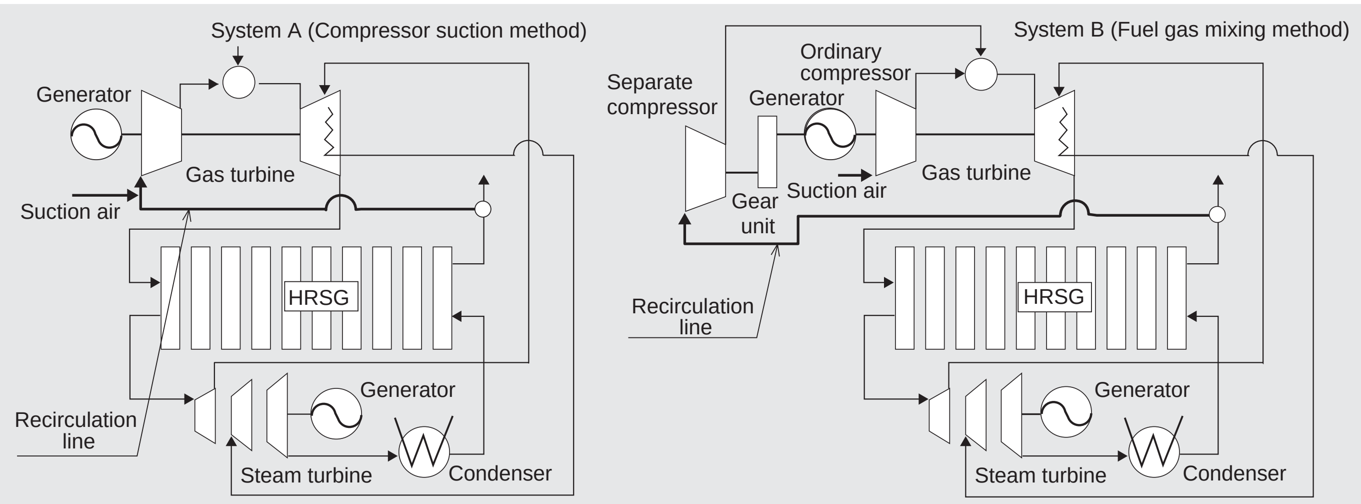


Fig. 2 Recirculation system

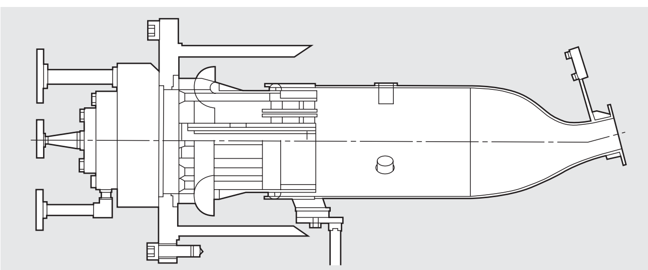


Fig. 3 Examination schematic of 1 700°C diffusion type combustor

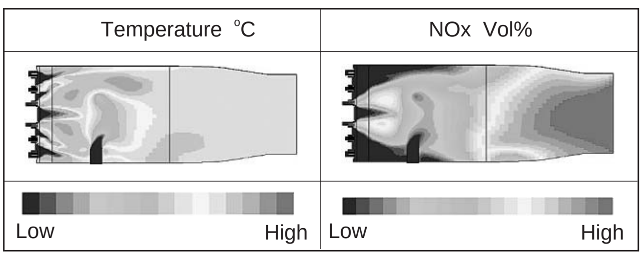


Fig. 4 Virtual images of temperature distribution and NOx concentrations by CFD in diffusion type combustor

In the case of the diffusion type combustor, the concentration distribution in the fuel mixing process was measured using the PLIF method. As a result, it was confirmed that sufficient mixing performance could be obtained at the outlet of the combustor. Furthermore, the estimation accuracy of the CFD for determining the degree of fuel and air mixing was experimentally verified. In the CFD estimation analysis of NOx at a temperature of 1 700°C, the lowest level NOx concentration could be obtained in the diffusion type combustor when the recirculation ratio was increased up to 3 % in O_2 concentration at the outlet of the combustor (**Fig. 5**).

3.2 Turbine-cooling technology

In the 1 700°C class gas Turbine, since the turbine blades are exposed to high temperature gas, the blades must be sufficiently cooled in order to maintain their durability. However, the increase of the amounts of cooling media (air and steam) results in a reduction in thermal efficiency. Accordingly, it is necessary to develop superior cooling technology that provides a higher cooling effect with a lower amount of cooling media. In order to solve this problem, a hybrid cooling system consisting of internal cooling structures by steam which has higher heat transfer coefficient and by film air cooling which has capability of reducing the thermal load on the turbine blades and vanes was applied (**Fig. 6**).

During the first fiscal year of the project, the development of the component technology to be used in the air cooling system was studied. For example, in the transpiration cooling system, a method combining a porous material and full coverage film cooling was studied through a heat transfer test. As a result, cooling performance more uniform and higher than that of any conventional cooling method could be obtained (**Fig. 7**). It is expected that the roofed film cooling system will be able to ensure a uniform and wider film to provide higher cooling performance (**Fig. 8**) through the fluid dynamic analysis. In the future, MHI will actively develop the technologies necessary for practical use in cooling systems, including additional advanced cooling technologies for blades and vanes for the 1 700°C class gas Turbine.

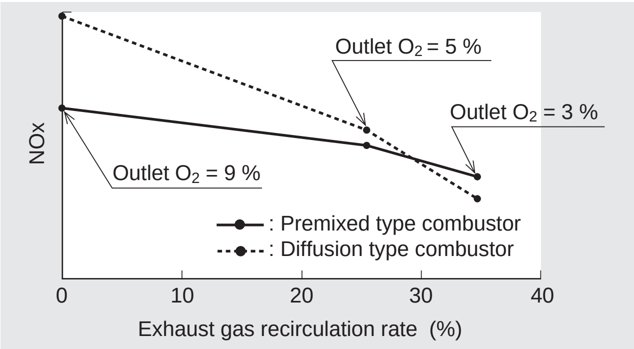


Fig. 5 Estimation of emitted NOx by CFD

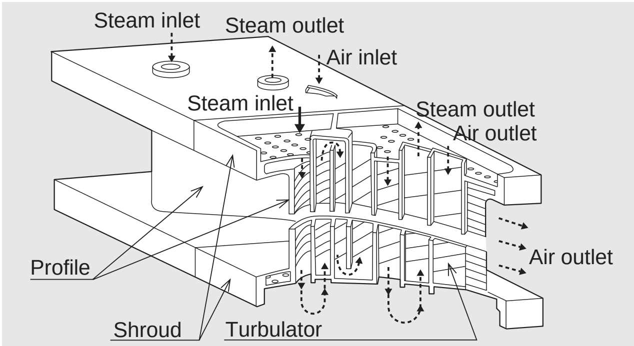


Fig. 6 Conceptual view of cooling system of first stage stationary vane of turbine

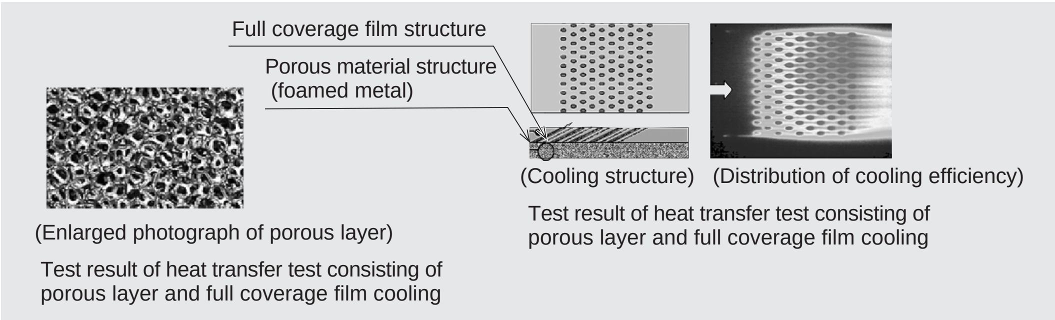


Fig. 7 Example of transpiration cooling system

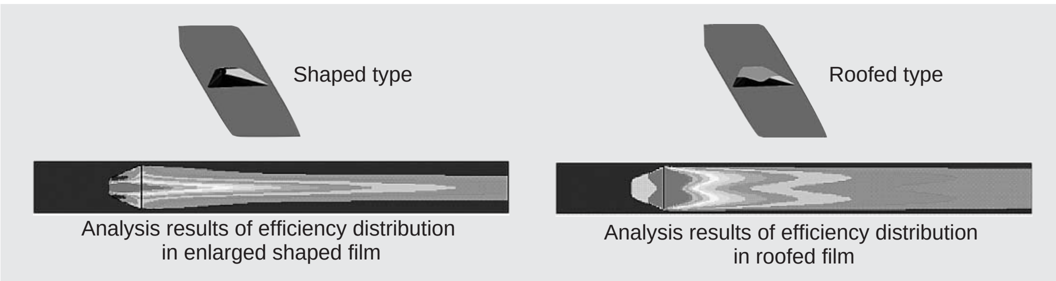


Fig. 8 Analysis result of new type film cooling

3.3 Super heat resistant material technology

In order to develop the 1 700°C class gas Turbine, it is essential to develop effective heat resistant materials as well as turbine cooling technologies and thermal barrier coating (TBC) technologies. In order to develop the actual 1 700°C class gas Turbine, alloys having superior acid resistance, high temperature creep strength, and thermal fatigue strength, as well as casting stability must be developed. Accordingly, the high temperature properties such as the creep rapture strengths, thermal fatigue strengths, and oxidation resistances were evaluated based on the second generation and third generation Ni-base single crystal alloys developed by the Super Heat Resisting Material Group of NIMS(1)(2). Then the casting test of these alloys was performed. The alloys used for these various tests consisted of TMS-82+ (second generation alloy) and TMS-75 (third generation alloy) developed by NIMS, existing CMSX-4 (a second generation alloy), and alloys being investigated for further improving theses alloys.

(1) High temperature strength

Fig. 9 shows the improved creep rupture strengths of these new alloys, comparing them with that of existing MGA1400DS. Any of the single crystal (SC) alloys shows higher strength, owing to the high γ' phase volume rates and the effect resulting from the addition of Re. TMS-82+ in particular has excellent strength characteristics that satisfy the development goals required as a material for the blades of the 1 700°C class gas Turbine. With regard to thermal fatigue strength, a test aimed at reproducing the overlap of creep damage (compression) was carried out, taking into consideration actual usage conditions. As a result, alloy C with excellent thermal fatigue strength characteristics was found, among results which were generally unsatisfactory in improving the existent alloy, as shown in the typical example of **Fig. 10**. In the future, MHI intends to move ahead with trying to achieve further improvements as well as conduct further longer term evaluations, on the basis of the results obtained in this study. For reference, it is noted that the effect of the thermal fatigue strengths on the overlap of compression creep in SC alloys has also been reported in other papers(3).

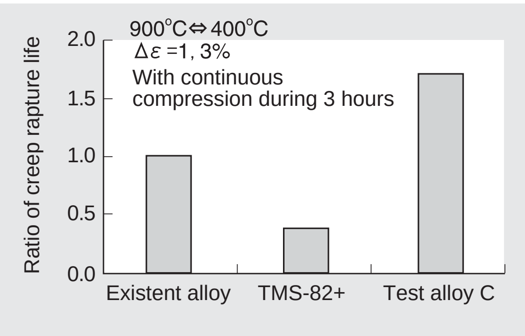


Fig. 10 Thermal fatigue test result for each alloy

(2) Oxidation resistance

The oxidation resistance of the actual blades is achieved through the use of the coating method described later. In addition, the oxidation resistance, which is a basic property of the blade material, was evaluated by heating the blades in the atmosphere. As a result, it was demonstrated that any of the alloys has excellent oxidation resistance compared with the existing alloy. The investigated alloy B had remarkably excellent qualities in this regard (**Fig. 11**).

(3) Casting test

Casting is an important step in the manufacturing process of turbine blades and vanes. It is important to establish casting parameter which ensure sound blade materials and that can result in obtaining ever better casting yields. Consequently, casting tests and solidification analysis were carried out to evaluate the casting capability of each SC alloy and to define the range of each casting condition required to obtain sound SC structures. In addition, the trial manufacturing of actual full-scale large sized blades was carried out in order to accumulate basic casting technologies.

As a result of these development efforts during the first year of the project, it was confirmed that the alloys examined have the basic potential properties necessary, such as oxidation resistance, etc., as well as creep rupture strength for the blades. In the future, MHI continues these activities to achieve further improvements and development, based on these results.

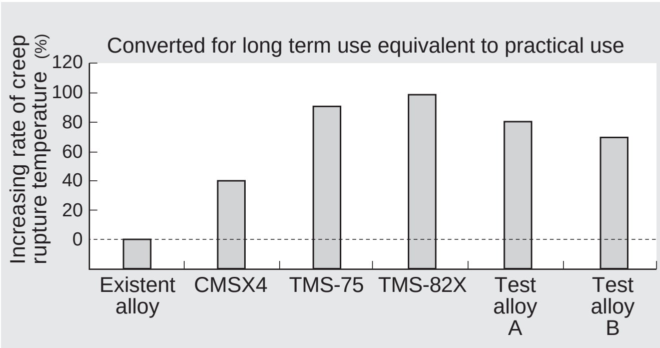


Fig. 9 Comparison of improvement in creep rupture temperature for each alloy

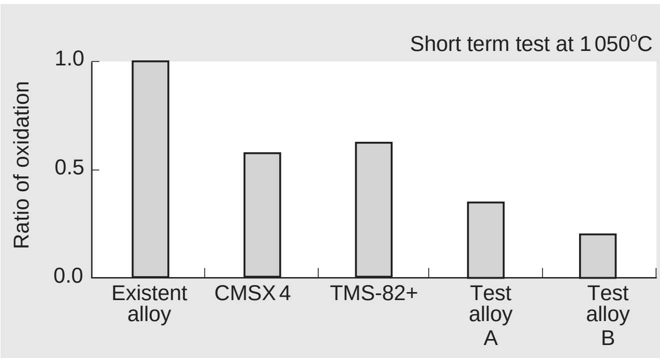


Fig. 11 Atmospheric oxidation test results for each alloy

3.4 Coating technology

The application of TBC is essential for ensuring the proper protection and reliable operation of the latest high temperature gas turbines.

Fig. 12 shows an illustration of the thermal barrier effect of TBC. Generally, the temperature of the metal is reduced by applying ZrO_2 type ceramics, which is low in heat conductivity, as a top coating after applying the alloy MCrAlY (M means Co, Ni, CoNi, and similar metals) with its excellent oxidation resistance characteristics, as a bond coat to components to be cooled. ZrO_2 type ceramics, which is abbreviated as YSZ (yttria partially stabilized zirconia) consists of ZrO_2 that is partially stabilized with 8 wt % Y_2O_3.

In order to improve the performance of the 1 700°C class gas Turbine, the surface temperatures of the top coat and the temperature of the bond coat are higher than those in conventional high temperature gas turbines. Under these conditions, the materials used at present are insufficient as a thermal barrier property and the reliability of these materials are also insufficient due to the deterioration of material properties.

Various materials were developed for the top coat that had low heat conductivity characteristics, according to the flowchart[4] shown in **Fig. 13**. Heat conductivity was used as an index for improving the thermal barrier performance, and the coefficient of linear expansion was used as an index for increasing break away resistance. That is, with the aim of developing an oxide type material with a melting point of 2 000°C or higher, some candidate materials were extracted by using the first principle band calculation. The ceramics materials selected by this material calculation were ZrO_2 type ceramics, whose stabilizing agent is changed from the usual Y_2O_3 to lanthanoid type heavy rare earth metal oxides, and compound ceramics with complex crystal structures.

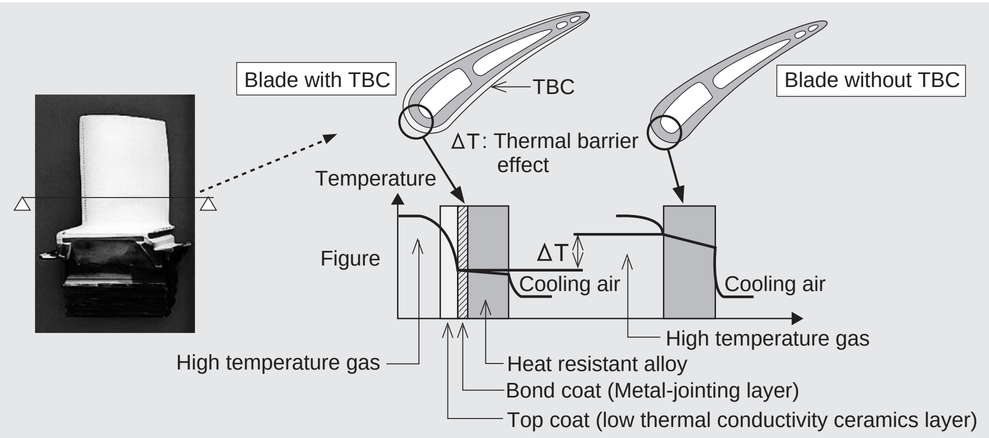


Fig. 12 Thermal barrier effect of TBC

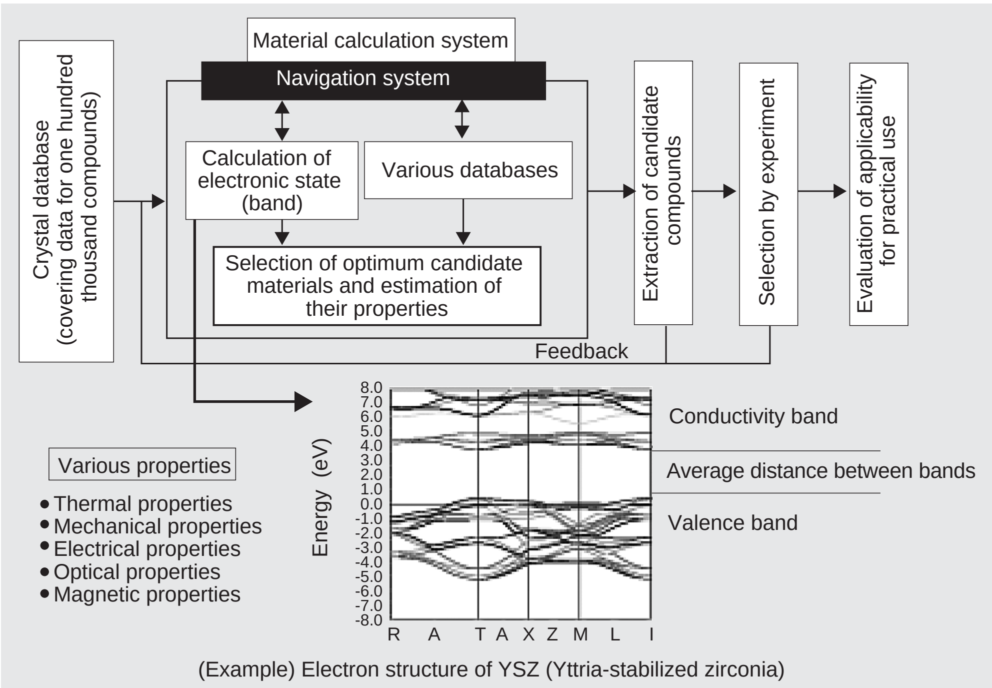


Fig. 13 Flowchart of development of top coat material, utilizing first principle band calculation

Then, the properties of selected sintered materials that were provided for these materials were respectively measured. **Fig. 14** shows the measurements of the heat conductivities of the selected materials (sintered materials). Any of these selected sintered materials showed lower heat conductivity than that of the YSZ (ZrO_2-$8Y_2O_3$) used at present. At the same time, the coefficient of linear expansion, Young modulus, and high temperature crystal stability of each material were evaluated to confirm that these figures are equivalent to or higher than those for YSZ.

In developing a bond coat with excellent oxidation resistance, an oxidation test in atmosphere was carried out on respective materials. These materials consisted of NiCrAlY, which is commercially available and has excellent oxidation resistance characteristics, NiCoCrAlY-Re, developed by MHI, and diffusion-treated material, CoNiCrAlY+Al, as well as CoNiCrAlY, which is generally used as a bond coating material for industrial gas turbines. **Fig. 15** shows the results observed of the oxidized scales present after the tests. The figure shows that the growing rates of the oxide scales are slower than that of the existing material, and that the oxidation resistance of all of the developed materials is improved.

In the future, MHI intends to proceed with the development of the fundamental technologies for granulating thermal spraying powder and flame spray coating as well as the development of new top coat and bond coat materials, based on the above mentioned results, and to evaluate the suitability of these materials as TBC.

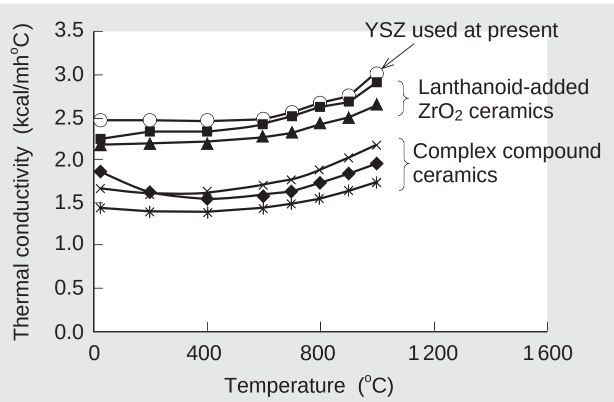


Fig. 14 Results of measurements of thermal conductivity of trial manufactured sintered ceramics

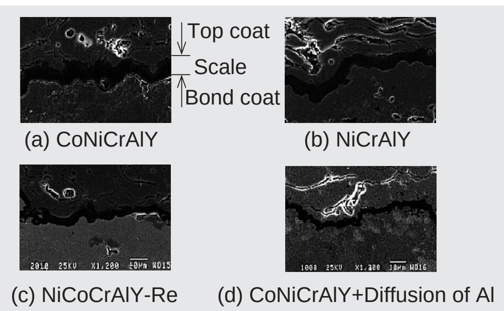


Fig. 15 Observation results of oxide scales after oxidation test of various bond coats (1000°C x 1000 h)

3.5 High load high performance turbines

The aerodynamic design conditions in the 1 700°C class gas Turbine are extremely severe. The pressure ratio increases to 1.5 times or more of conventional turbines, and the aerodynamic load factor reaches approximately 1.3 times that of conventional turbines. Efficiency in the conventional technology inevitably decreases under such severe conditions. In this project, an efficiency increase of 1 % is targeted by developing a new concept. The following research and studies were conducted during the first year of the project.

(1) The basic configuration of a high load and high performance turbine was preliminarily investigated, with consideration given to distributing the load to every blade evenly to the extent possible, taking into account restrictions in strength (**Fig. 16**).

(2) In investigating the high load and high performance blade profile, the turning angle was set to be about 120° and the blade profile thickness is selected as thick enough to contain the cooling structures.

(3) Experiments based on component models and CFD analysis were performed in order to gain a better understanding of the phenomena involved, with the aim of reducing the interference caused in the flow field between the blade and end wall. As a result, the behavior of horseshoe vortexes originating from the leading edge of the turbine blade was clarified. In the future, MHI intends to proceed with the investigation of losses based on the knowledge gained through this project.

(4) Cascade test of turbine blades and vanes

The profile losses in the high load cascade was 3.2 %, and the losses due to secondary flow was about 5%. These figures almost agree with the results obtained by estimation analysis. In the first year of the project, the cascade tests were performed on the basic flow path profile and on the high load and high performance blade profile that were developed during this time. The results obtained were nearly as estimated. There brought out some technical issues of an unsteady flow on the convex side of the blade and technical issues in case that the asymmetric end wall were applied to the high load blades as shown in **Fig. 17**. A design concept for reducing the interference between the blade and the end wall is being developed, including the non-steady state and three-dimensional design, based on the results obtained thus far.

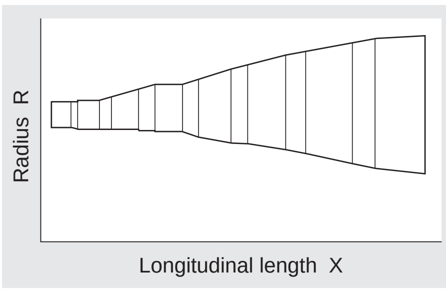


Fig. 16 Profile of turbine flow path

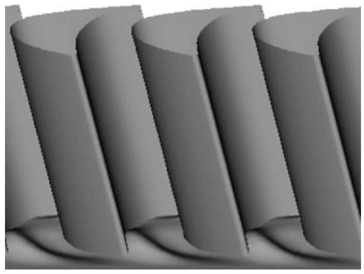


Fig. 17 View of high load blades and contoured end walls

3.6 Development of high-pressure ratio and high-performance compressors

One of the purposes of this project is to create the design concept for a compressor that would be higher efficiency rather than the current compressor with minimized number of stages under the high pressure conditions of the 1700°C class gas Turbine which is higher than that of conventional compressors with a pressure ratio of 25. During the first year of the project, the study focused on new transonic blades applied to the front stages and on new subsonic blades applied to the middle and rear stages.

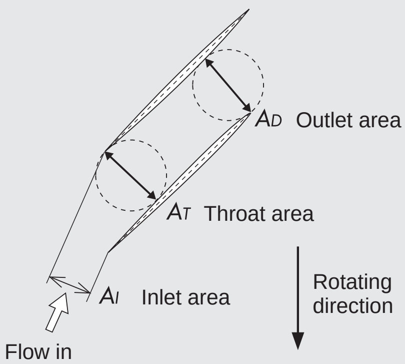
(1) Investigation of transonic blades for front stages

In order to design a blade profile that minimizes shock wave losses, blade profile parameters defining the shock wave structure were extracted. **Fig. 18** shows the shock wave patterns in which such losses are minimized. In addition, it was confirmed that the shock wave structure can be controlled three-dimensionally by improving the stacking method of the blade section. In this study, it was confirmed that the most outstanding improvement in the performance and excellent atmospheric temperature characteristics are achieved by the forward sweep blade with a blade tip, as shown in **Fig. 19**.

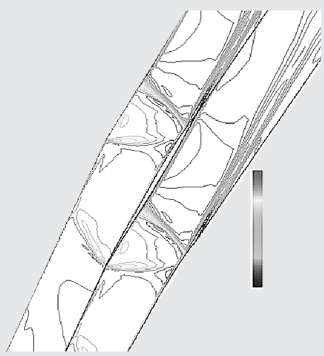
(2) Investigation of subsonic blades for middle and rear stages

In order to increase the load and efficiency of the middle and rear stages, the blade profile, the stacking method of the blade section, and the minimization of interference between the cascades were investigated. In the process of this investigation, the means for improving the performance and for assessing the improved performance at the present stage of investigation were confirmed for each improvement method.

Fig.20 shows a comparison between the conventional and new designs of the stationary vanes. This figure shows that stream lines are controlled at an area of about 20% distant from end wall.

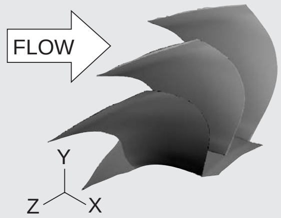


(a) Profile parameters for controlling shock waves

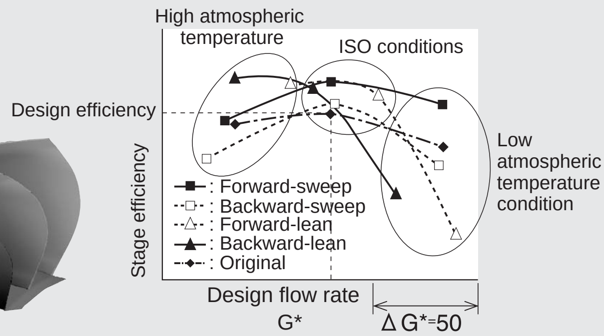


(b) Shock wave pattern with minimum pressure loss

Fig. 18 Pattern of shock waves with minimum pressure loss

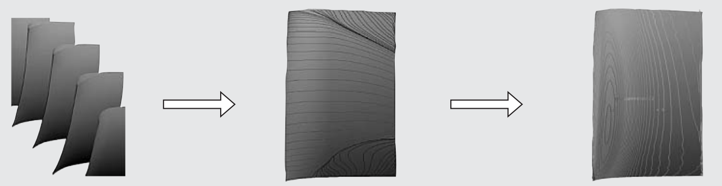


(a) Forward sweep blade



(b) Corrected mass flow rate & stage adiabatic efficiency curve

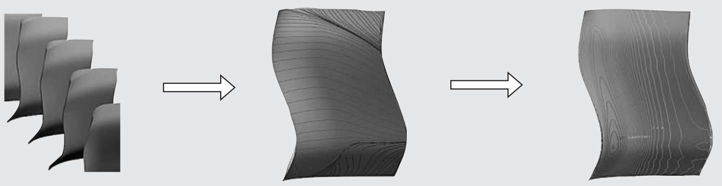
Fig. 19 Investigation of three-dimensional blade



(a) Conventional vane profiles

(b) Stream lines on convex side

(c) Static pressure distribution on convex side



(a) Advanced three-dimensional profiles

(b) Stream lines on convex side

(c) Static pressure distribution on convex side

Fig. 20 Comparison between conventional stationary vane and newly designed three-dimensional stationary vane

4. Present status and future of gas turbine

In addition to the development of super high temperature gas turbine described above, MHI has a well established track record of experience in effective utilization of by-product gases in oil refineries and blast furnace gases in ironworks. The construction work of a coal gasification gas combined power plant as a national project is proceeding steadily to start test operations in 2007. The combination of gas turbines and fuel cells is also being investigated with the aim of achieving further improvements in combined thermal efficiency. In addition, MHI is also actively involved in the study of CO_2 closed cycle system recycling of exhaust gas that does not result in NOx emissions as part of another national project.

5. Conclusion

This paper described the contribution being made to the global environment through the development of the 1 700°C class super high temperature gas Turbine that is expected as a leading machine in the future of gas turbine combined plants. The research and development into various component technologies for the gas turbine requires further continuous investigation. Furthermore, verification of the effective operation of these systems in a practical size machine is essential in order for these technologies to be commercialized. To achieve this goal, the cooperation of government, utility companies, and machine manufacturers on a national level is important. Only this approach can open the door to realizing further contributions to the global environment.

References

(1) T.Hino, H.Harada et al., Proc.of Intern. Gas Turbine Congress 1999 Kobe, November (1999) p.169
(2) Y.Koizumi, T.Kobayashi, et al., Materials for Advanced Power Engineering (1998) p.1089
(3) H.Zhou, M.Osawa, et al., Superalloy 2004 (2004) p.225
(4) Akiyama et al., New Oxide Materials for Thermal Barrier Coating, Ceramics Vol.39 No.4 (2004) p.300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