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DEVELOPMENT OF KEY TECHNOLOGIES FOR THE NEXT GENERATION HIGH TEMPERATURE GAS TURBINE

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ABSTRACT

Global warming is being “prevented” by reducing power plant CO_2 emissions. We are contributing to the overall solution by improving the gas turbine thermal efficiency for gas turbine combined cycle (GTCC) . Mitsubishi Heavy Industries, Ltd. (MHI) is a participant in a national project aimed at developing 1700°C gas turbine technology. As part of this national project, selected component technologies are investigated in detail. Some technologies which have been verified through component tests have been applied to the design of the newly developed 1600℃ J-type gas turbine.

INTRODUCTION

Global warming is being “prevented” by reducing power plant CO_2 emissions. We are contributing to the overall solution by improving the gas turbine thermal efficiency for gas turbine combined cycle (GTCC). MHI is a participant in a national project to develop 1700°C gas turbine technology. As part of this national project, six component technologies such as combustion, cooling technology, Thermal barrier coating, heat resistant superalloy and aerodynamics of turbine and compressor are in development. This paper reviews the current status of the technical challenges related to those technologies.

Efficiency target and effect of CO2 reduction

Increasing the combustor exit temperature improves the combined cycle efficiency. Therefore, the target temperature for the next generation gas turbines is 1700°C. With this temperature, 62–65% (LHV) thermal efficiency on natural gas can be achieved as shown in Fig.1.

Improvement in the cycle efficiency contributes to a reduction in the amount of CO_2 emissions from power plants. An estimation of CO_2 reduction can be calculated as follows: Assuming that the efficiency and the CO_2 emission of the conventional coal-fired power plant is about 44% (LHV) and 0.84kg/kwh, respectively; the CO_2 emission from a 1250MW coal fired power plant is about 8.4 million tons per year (8000/hr). An equivalently sized 1700°C natural gas fired combined cycle gas turbine with efficiency 62% (LHV) and CO_2 emission 0.32kg/kwh generates about 3.2 million tons per year. Therefore, replacing just one conventional power plant with the 1700°C combined cycle plant reduces the emissions by 5.2 million tons. This is equivalent to 0.4% of Japan’s total CO_2 emission in 1990, 1.26 billion tons.

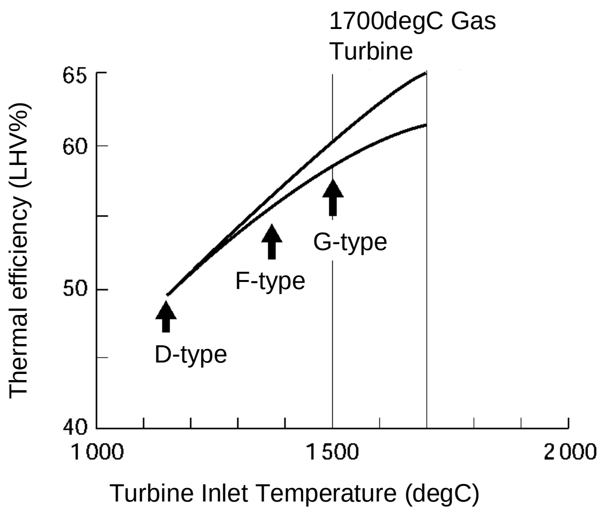
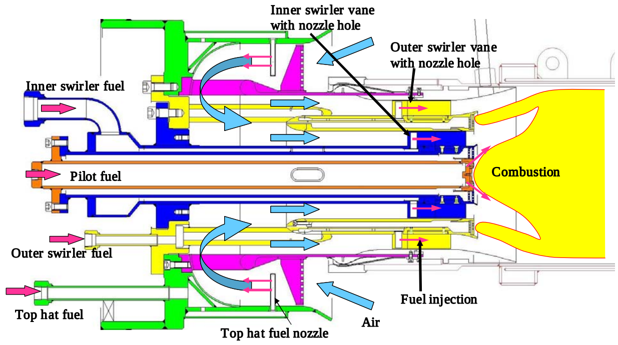


Fig.1 C/C efficiency and turbine inlet temperature

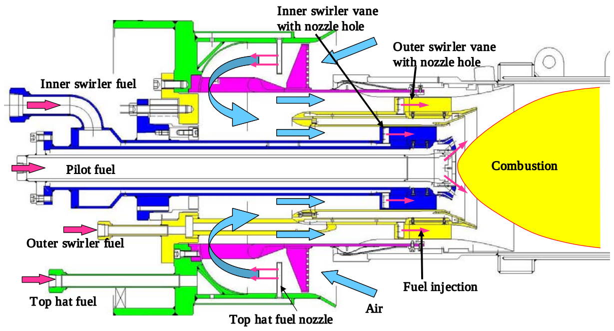
COMBUSTOR WITH EXHAUST GAS RECIRCULATION SYSTEM

In order to reduce NOx emission generated in high temperature combustion zones, the exhaust gas recirculation (EGR) is one of the most effective methods for extremely high temperature combustion system such as 1700℃ class gas turbine combustor. The low oxygen condition with EGR has the reliable capability to suppress the generation of NOx.

Figure 2 shows the sketch of the combustors under development. The double flame concept in figure 1(a) applied to a previous combustor is effective in order to make flame stabilize. However, because of the outer flame close to the wall, the wall temperature has the tendency to be high with double flame concept, and it would shorten the combustor life cycle. To make a countermeasure against such a risk, the combustor with the single flame concept is shown in figure 1(b). The outer flame is eliminated by the smooth conjunction of pre-mixed flows from both of outer and inner nozzle passages.



(a) concept1(double flame)

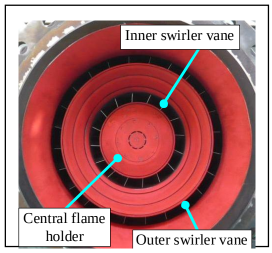


(b) concept2(single flame)

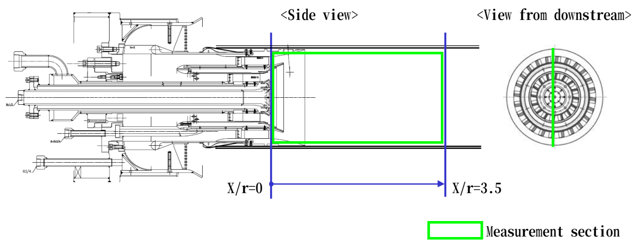
Fig. 2 Combustor Conceptual Diagram

These combustors have the coaxial double swirler structure. The fuel flow path is formed by the cavity in the swirler vane. The fuel is supplied through the fuel cavity onto the surface of swirler vane forming a fuel-air mixture. Uniformity of mixing fuel and air is necessary to decrease NOx generation in the high temperature region. Swirler vanes with nozzle holes are improved to make fuel-air flow more uniform than previous design. Figure 3 shows the concept2 combustor test model seen from the downstream.

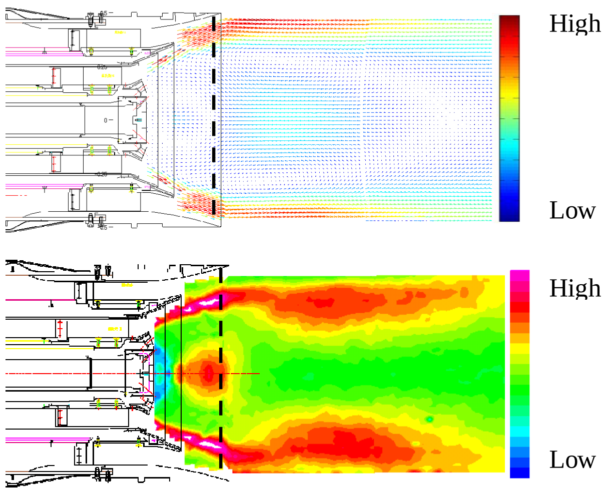
Fig. 3 Combustor test model (Red: Color of Thermo-paint)



The flow field of the concept2 combustor in the downstream area of flame holder was measured by particle image velocimetry (PIV), and the prediction accuracy with CFD was validated. Figure 4 shows the PIV measurement position, the visualized data and Fig.5 shows the comparison with two kinds of CFD. Large Eddy Simulation (LES) showed better agreement with the PIV result than Reynolds Averaged Navier-Stokes(RANS) simulation did.

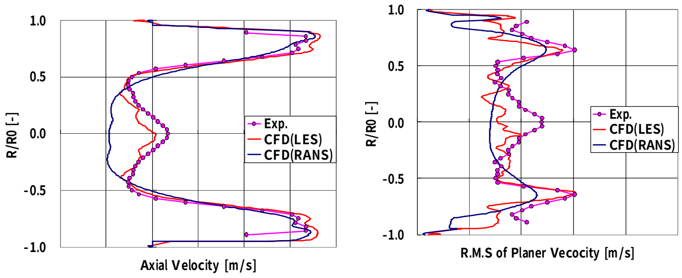


(a) Schematic of PIV Measurement Section



(b) Measured data(Upper : Axial velocity, Lower: RMS of velocity fluctuation)

Fig. 4 PIV Measurement



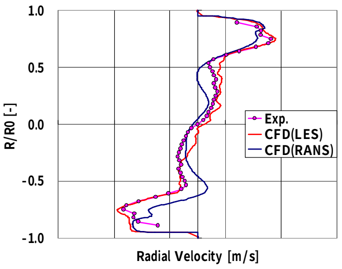


Fig. 5 CFD validation with PIV data

Figure 6 shows the EGR combustion test rig in order to examine the series of experiments which test the different pressure which range from 0.16MPa to 0.37MPa. The diffusion combustor is set in upstream side from the test combustor to simulate the low oxygen condition.

Figure 7 shows the trend of CO at the combustor outlet, as the combustion pressure changed. CO decrease as the combustion pressure rise. CO of concept1 combustor is almost the same as the original. Although the CO of concept2 combustor is slightly higher than the former, the CO at actual pressure condition is estimated to be less than the target level.

Figure 8 shows NOx estimated for the actual plant pressure. Due to the improvement of the fuel concentration distribution, NOx of the concept1 and concept2 combustor are less than that of the original combustor. Target NOx50ppm is expected to be satisfied with the design oxygen condition at actual plant pressure. These estimations are based on numerous combustor data which have been measured in actual power plants.

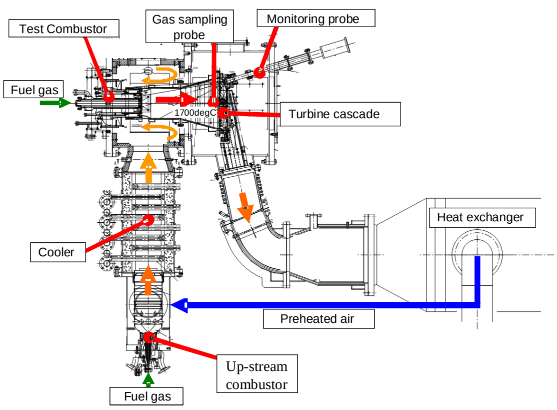


Fig. 6 System diagram of combustion facility with simulated exhaust gas recirculation (EGR)

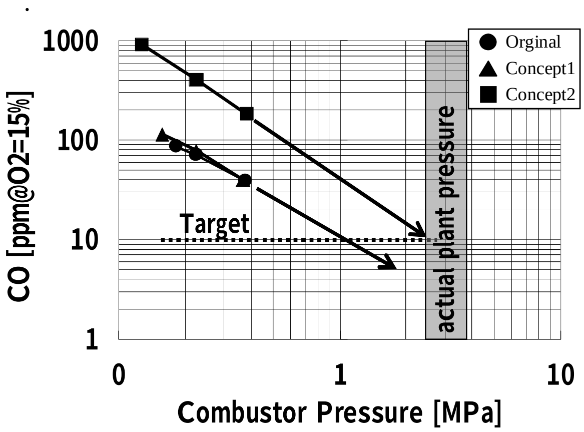


Fig. 7 Combustion test results of CO concentration with combustor pressure

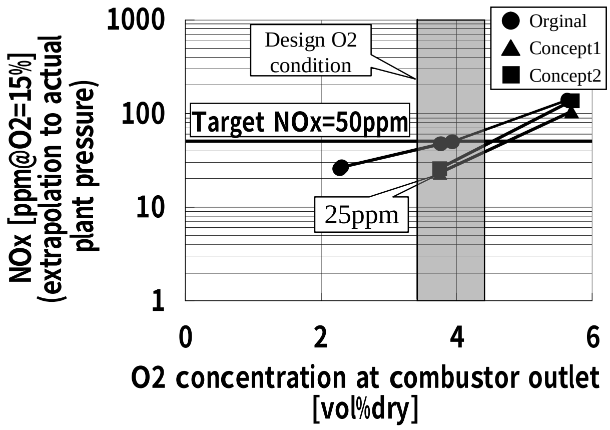


Fig. 8 Intermediate-pressure combustion test results (NOx Concentration vs. Oxygen Concentration at Combustor Outlet)

TURBINE COOLING TECHNOLOGY

1700°C class gas turbine blades are exposed to high heat loads and thermal stresses. Therefore, high performance cooling schemes which only use a small amount of cooling air are required to extend turbine blade life without significant loss of thermal efficiency. In this paper, an advanced study of a film cooling system has been described.

Film Cooling on a Rotating Blade Tip

The film cooling effectiveness on a rotating blade tip was measured with PSP (pressure sensitive paint) technique based on a mass-heat transfer analogy which allows for detailed evaluation of film cooling effectiveness. Figure 9 shows the schematic drawing of a rotating model turbine as the turbine test rig. In this study, which was conducted at low speed but still maintained similar velocity triangles to those of the real turbine at the correct operating conditions; very complicated flow features, induced by tip leakage, secondary flows, rotating effects, and wake generated by forward vanes, affecting the film cooling effectiveness on the tip region were simulated. The stream line on a tip surface with CFD is shown in Figure 10. The leakage flow due to pressure gradient across the tip was obtained.

The photograph of test blades is shown in Figure 11. Two kinds of measurement blades, which have a squealer at suction side and film cooling holes at pressure side and tip surface, were prepared. One of the test blades has shaped film cooling holes at pressure side.

Figure 12 shows the film cooling effectiveness contours on the tip surface. Purge-to-mainstream mass flow ratio of film cooling flow is 0.1%. Film cooling flow along the stream line in Figure 10 were obtained. The lateral spreading of the film cooling flow in shaped film cooling hole is improved, compared with that in cylindrical one. The advantage of shaped film cooling hole has been confirmed on a rotating blade tip as is usually expected on profile surfaces.

Film Cooling around Leading Edge

Sensitivity of film cooling mass flow rate on a cooling characteristic around a row-1 vane leading edge was investigated because it is exposed to very high heat load in the turbine and any prediction errors lead to more significant damages in 1700degC operation compared to current engine condition. The test was carried out under high Reynolds number and Mach number condition equivalent to real engine condition.

Figure 13 shows the cascade consisting of 3 turbine vanes. The center vane is measurement one with film cooling holes at leading edge. The surface of measurement vane is sprayed with PSP as is used in the measurement on a rotating blade tip. The cascade shown in Figure 12 is installed in high speed cascade test facility. Turbulence level of mainstream is controlled by turbulence grid in the facility.

Figure 14 shows film cooling effectiveness contours under design and 10 percent reduced showerhead injection. Relatively high film cooling effectiveness at the suction side around leading edge has been confirmed. On the other hand, low film cooling effectiveness around the tip region is attributed to the horseshoe vortex rolling up the inlet boundary flow.

Figure 15 shows distribution of film cooling effectiveness at the mean section of pressure side. Approximate 0.02 of film cooling effectiveness has been confirmed between design and reduced cooling air condition. This is equivalent to higher gas temperature on the surface by more than 20degC. With this data, reduction of cooling air will be investigated after the verification hot cascade tests in near future.

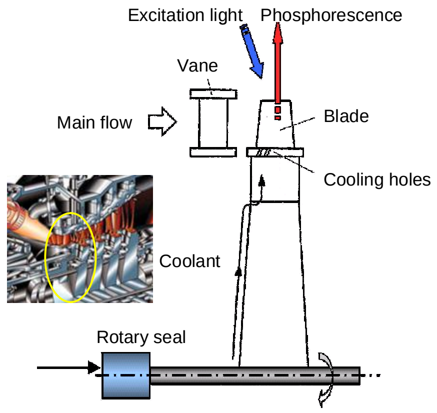


Fig.9 Rotating rig for film cooling system evaluation

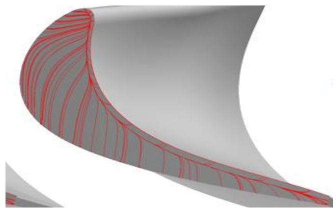


Fig.10 Stream line on a tip surface with CFD

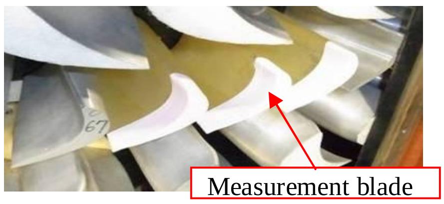


Fig.11 Test blade

(a) Cylindrical hole

(b) Shaped hole at pressure side

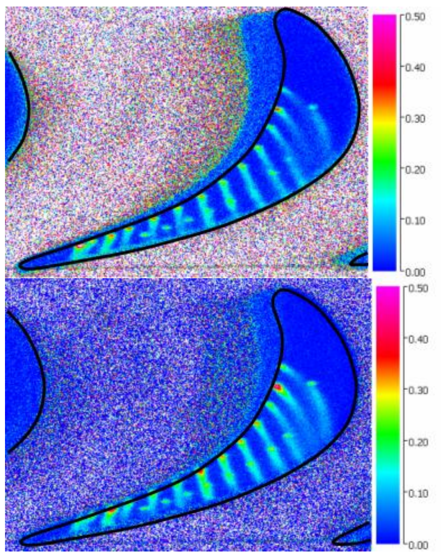


Fig.12 Film cooling effectiveness contour on the tip surface

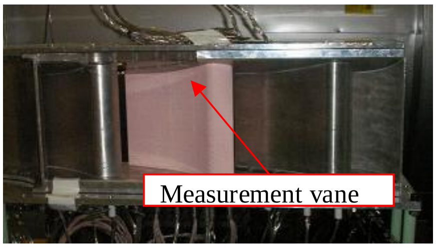


Fig.13 Linear cascade for high speed cascade test

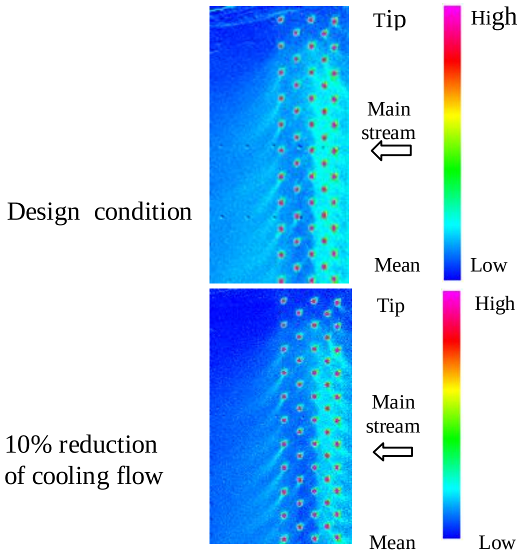


Fig.14 Film cooling effectiveness contour at leading edge and pressure side

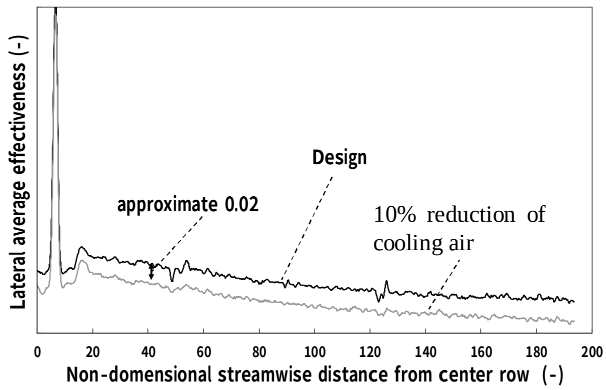


Fig.15 Distribution of film cooling effectiveness at the mean section of pressure side

SUPER HEAT RESISTANT MATERIAL TECHNOLOGY

Essential material properties for the industrial gas turbine blade, such as creep rupture strength, thermal fatigue strength, and oxidation resistance, were tested with improved superalloys based on the second and third generation Ni-base single crystal superalloys, which developed by the National Institute for Materials Science (NIMS).

At the operating conditions of the industrial gas turbine blades, creep strength and thermo-mechanical fatigue strength are most important properties. However, creep strength and fatigue strength are reciprocal properties; namely, it is difficult to improve the both of properties in parallel. To get over this difficulty, alloy design program by NIMS was utilized.

Figure 16 shows results of the tests. Both thermal fatigue strength and creep strength of the experimental alloy satisfied the development target. It was confirmed that the results of strength tests about this developed alloy were reproducible within tolerable scatter band through a number of tests. Fine square γ' phases precipitated in the developed alloy. It was suggested that the excellent strength properties of developed alloy was caused by the microstructure.

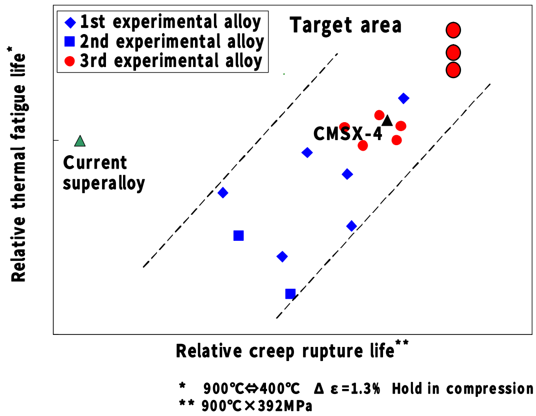


Fig.16 High temperature strength of evaluated superalloys

Since the oxidation resistance of the actual blades was one of the important properties, it was evaluated by heating tests in the atmosphere. Figure 17 shows the weight increase of each superalloy after oxidation test at 1050℃. Figure 18 shows cross-sectional microstructure near surface after oxidation tests. The results show that the tested superalloys have better oxidation resistance than that of conventional superalloy. It seemed that anti-oxidation properties of the superalloy were due to the formation of an oxidation protective film thicker than that of CMSX-4 observed in Fig.18 by effective constituents.

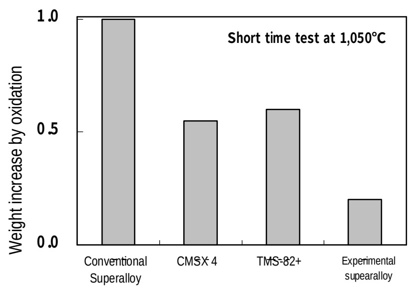


Fig.17 Oxidation test results for each superalloy

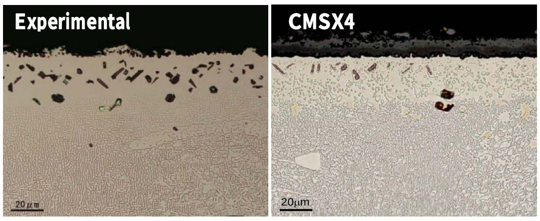


Fig.18 Microstructure of near surface after oxidation test

HIGH EFFICIENCY HIGH LOADING TURBINE

To accomplish high CC efficiency, improvement of turbine efficiency is one of the most important subjects to be examined. High performance three dimensional airfoils, three dimensional end-wall profiling, and a new clocking concept between transition pieces and row 1st vanes had been examined and developed. These were described in previous reports.

In order to apply the three dimensional end-wall profiling, it it necessary to evaluate the heat load onto the end-wall in terms of effects of combination of concave and convex surfaces for high temperature condition.

Because of the high combustion gas temperature, the reduction of heat load, which results in the reduction of mass flow rate of cooling air, is effective to get high CC efficiency. Some ideas for the reduction of heat load have been examined. In this paper, related to this issue, a newly developed method to measure heat load onto the end-wall surface will be shown.

Figure 19 shows the concept for the method. The concept is very simple. The point of the method is to manufacture thin low heat conductive material layer on the thick high heat conductive material (ex. copper) block and to maintain thickness of the thin layer precisely. Figure 20 shows a specimen and configuration for flat plate test. This test was done to check the concept. Results with predicted values are shown in Fig.21. Although, because of 3-dimensionality of the flow, heat transfer coefficient on the surface is not constant in the direction perpendicular to the flow, the measured value on center line shows good agreement with the predicted values. This technique will be applied to the study of heat load reduction on the end-wall.

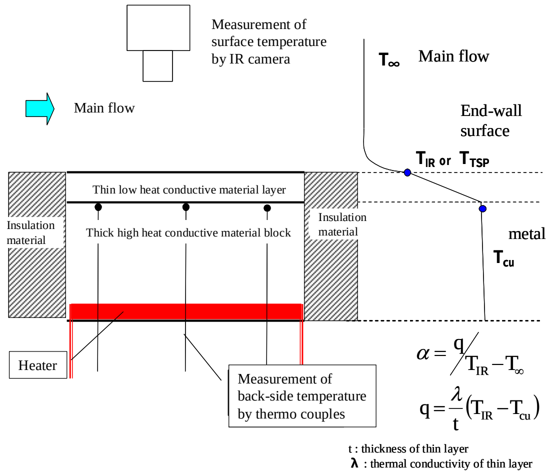


Fig.19 Sketch of the concept of method for heat load measurement

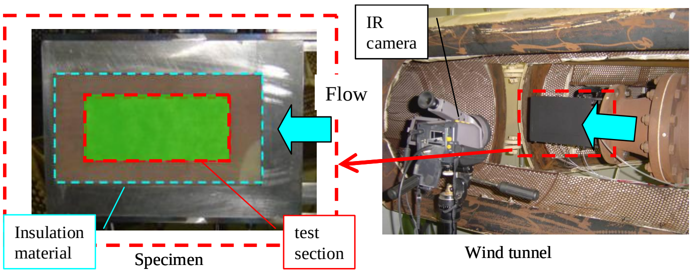


Fig.20 Test specimen and test configuration

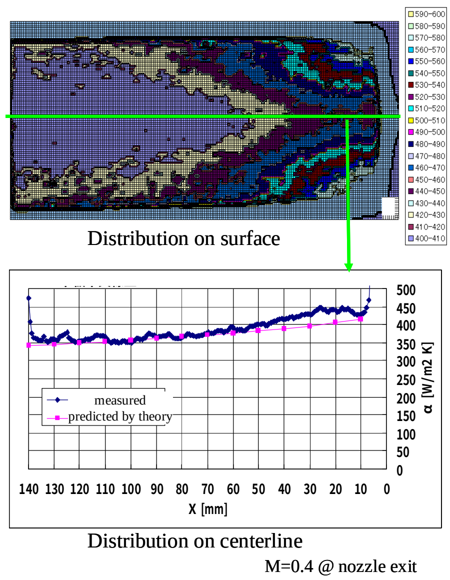


Fig.21 Heat transfer coefficient with predicted values

APPLICATION OF THE TECHNOLOGIES TO 1600degC GAS TURBINE (M501J)

Since some of the technologies have been verified through component testing rigorous enough for practical application as part of this national project, it was decided at Mitsubishi Heavy Industries, Ltd to apply these technologies to the 1600℃ gas turbine (M501J) design. Figure 22 shows the technical features of M501J gas turbine. The key technologies developed in 1700℃ project and applied to M501J are mainly for turbine portion; (a) turbine cooling technology, (b) coating technology, (c) high efficiency turbine.

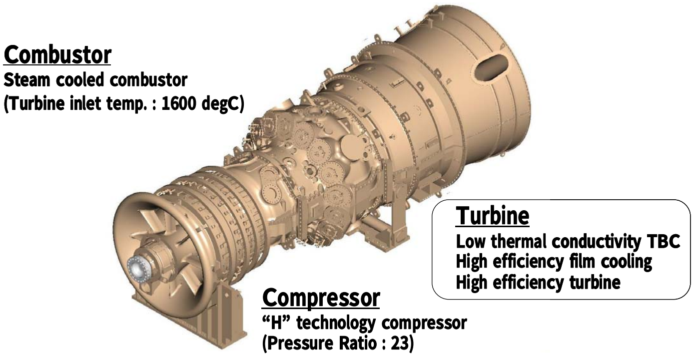


Fig.22 Technical feature of M501J gas turbine

CONCLUSION

In this paper, the newly developed technology for the 1700°C gas turbine was introduced. The research, part of the Japanese national project, was aimed at obtaining a thermal efficiency level of 62-65% (LHV) on natural gas.

The current status of the research project is summarized as follows:

(1) Combustor with exhaust gas recirculation system

For a given lean oxygen concentration for various pressure conditions, the NOx level during a 1700°C combustion test was under 50ppm (converted to actual pressure level). Unsteady PLIF and CFD were utilized to enhance the pre-mixing of the fuel. Especially, the LES simulation showed better prediction capabilities than the RANS currently used.

(2) Turbine cooling technology

Film cooling effectiveness of tip surface of rotating blades were measured in the rotating test rig. Valuable information, which could be used for a high-reliability cooling design, was obtained.

Also, sensitivity of cooling air flow was investigated for row-1 vane leading edge portion where heat load is high.

(3) Super heat resistant material

An advanced alloy with improved thermal fatigue life and longer creep rupture life was developed and its manufacturability was confirmed. Also, anti-oxidation characteristics were studied and the advanced alloy showed better results than widely used materials.

(4) High efficiency high loading turbine

To investigate the heat load on the three dimensionally designed end-wall, a measurement technique for heat flux distribution was studied with a fundamental flat plate test. It was confirmed that the method can be applicable for the future work.

Finally, some of the 1700°C gas turbine technologies have been considered to be applicable to the actual design and have already been applied to the design of the 1600℃ gas turbine (M501J) as reported previously.

ACKNOWLEDGMENTS

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