

Development and In-house Shop Load Test Results of M701G2 Gas Turbine

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ABSTRACT

Mitsubishi Heavy Industries, Ltd has developed upgraded M701G2 gas turbine. The M701G2 is a 3000rpm heavy-duty gas turbine designed to serve the 50Hz power generation needs for utility and industrial service. Net rated 484 MW with over 58% for 1x1 configuration.

The M701G2 combines the efficient, reliable design concepts of the M501F and the M701F with the latest low NOx combustion and the state-of-the-art cooling technology. The result is an advanced design, high temperature, efficient, low NOx, more powerful combustion turbine based on time proven reliable design concepts that will satisfy the large combustion turbine power generation needs for the next decade.

Across the board advances in computer technology have enabled manufacturers to improve analytical procedures in all aspects of design including stress analysis, heat transfer, aerodynamics, fluid mechanics, and structural dynamics. Metal temperature can be kept within the M701F experience by optimizing cooling system design.

The combustor is based on the successful dry low NOx combustor developed for the M501F/M701F. This combustor is presently operating at a 25ppm NOx level at 1400°C (2552°F) turbine inlet temperature. To achieve NOx levels of 25 ppm, the flame temperature has to be kept in the range of 1500-1600°C, Therefore, the M701G2 combustor uses steam cooling for transition piece to achieve the same NOx reduction

at the higher firing temperature.

Mitsubishi Heavy Industries, Ltd conducted the In house shop load test for M701G2 prototype engine in 2002 April. The result of this in-house shop load test is more than sufficient for design, reliability and performance verification. Test measurements verify that critical parameters such as shaft vibration, bearing oil temperatures, thrust loads, compressor starting characteristics, tip clearance and turbine blade metal temperatures are all well within design margins. The data also confirm that the overall operating capability and rating performance will meet or surpass predicted design performance. Next step will be a field installation for full load service testing and evaluation.

This paper describes the design features of M701G2 gas turbine and the results of the in-house shop load test.

INTRODUCTION

In the recent years, environmental issues such as achieving the target for reduced carbon dioxide emissions for combating global warming, discussed at the World Environmental Conferences, have become the worldwide assignment. Along with the issues, energy saving has been promoted all over the nations. In thermal power plants, combined cycle plants that utilize the steam recovered from gas turbine and turbine exhaust gas as the source of drive for steam turbine have come under the spotlight. The combined cycle plant is a promising

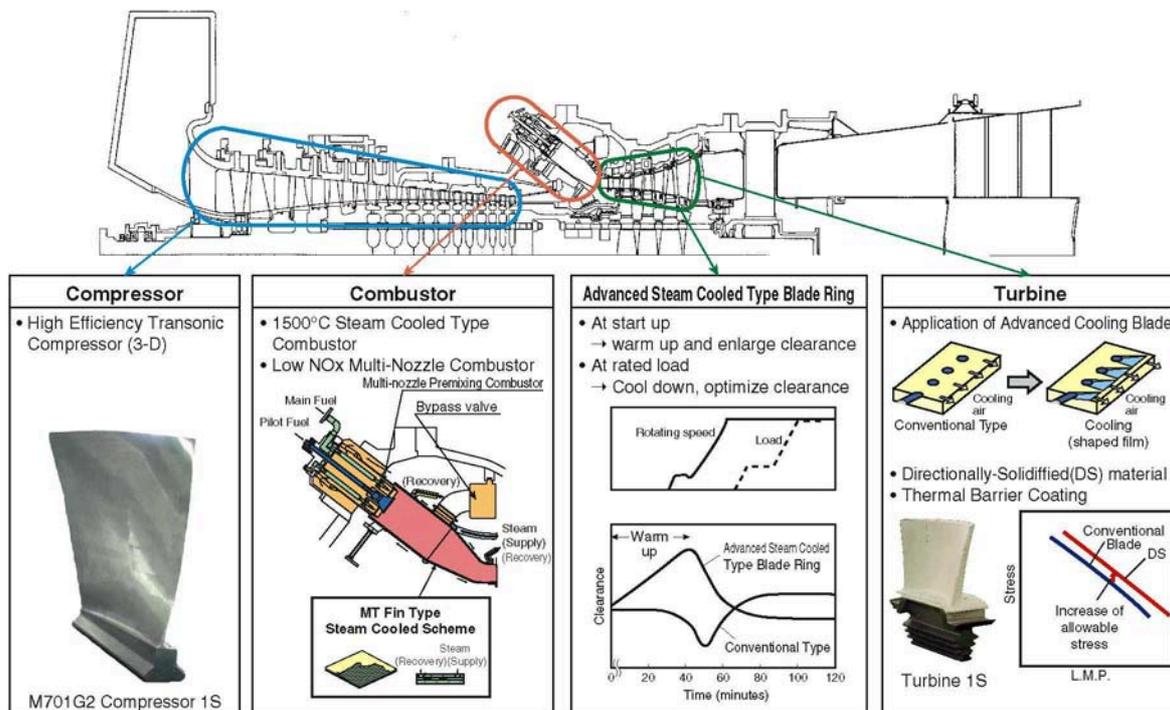


Fig. 1 Mechanical Characteristics of M701G2 Gas Turbine

technique that brings a higher thermal efficiency by achieving higher temperature and better performance of the gas turbine. It is not only being economical but also contributes dramatically to the reducing of carbon dioxide emissions.

With the installation of a high-capacity combined cycle plant, M701D Type gas turbine with the inlet temperature of 1150°C-class as its main unit, to Unit 3 Series in Higashi Niigata Thermal Power Plant of Tohoku Electrical Power in 1984 for the first case in the world, Mitsubishi Heavy Industry had attained the highest thermal efficiency of 48.6% (LHV)(44% HHV)

After the development of M501F/M701F Type gas turbine with the inlet temperature of 1350°C-class in 1989, more than fifty-five units are under operation as the main unit of combined cycle. In addition, the first 1500°C-class M501G gas turbine for 60Hz utilities was developed in 1997; in June it was put to operation in the long-term reliability verification system and has been operating in good performance. In July 1999, the first industrial G Type gas turbine M701G1 for 50Hz utilities was put to operation in Unit 4 Series in Higashi Niigata Thermal Power Plant of Tohoku Electrical Power Co., INC., and has been operating for over 20,000 hours. Moreover in 2001, Type M501H gas turbine was installed to the long-term reliability verification system, reached the full load and succeeded in verifying steam-cooled type gas turbine of the blades and vanes for the first time in the world.

With all these experience in developing gas turbines, Mitsubishi Heavy Industry has further completed the development of Type M701G2 for 50 Hz, aiming for the world highest-capacity and the best efficiency. In April 2002, the in-house shop load test was implemented. Special measurement system with 1800 measurement data installed, and it was verified excellent mechanical characteristics and performance as shown in this report.

Design feature of M701G2 Gas Turbine

The Performance of M701G2 gas turbine is shown in Table 1. As for 1 on 1 combined cycle, the output is over 480 MW and the combined efficiency is over 58% (LHV).

The design feature of M701G2 is shown in Fig. 1

In order to achieve the high level performance, various state-of-the-art technologies have been adopted to M701G2.

Compressor

The compressor of Type M701G2 has 14 stages with the pressure ratio of 21:1, and is a scale-design of M501H, which was tested in long-term reliability verification plant in Takasago Machinery & Works (T-point Project plant) in the year 2001. To maintain a good characteristic during start-up, variable vanes are installed in the front five stages, and to improve the part load operation performance for the combined cycle operation, it is equipped with inlet guide vane.

Also, to achieve its high efficiency and large air intake air flow, Multiple Circular Arc Airfoil (MCA) is adopted to the 4 front stages of the rotor, and Controlled Diffusion Airfoil (CDA) is adopted to the rest of the rotors and vanes.

The performance of the scale-designed compressor which are designed by the latest 3-D instrumentation code was verified in the test result of M501H in T-point Project plant.

Combustor

The combustor is base on the successful dry low NOx combustor developed for the M501F / M701F. This combustor is presently operating at a 25 ppm NOx level at 1400 °C (2552 °F) turbine inlet temperature. To achieve NOx levels of 25 ppm, the flame temperature has to be kept in the range of 1500 ~ 1600 °C, by supplying all air into the combustion zone, as shown in Fig.2. Therefore, the M701G

combustor uses steam cooling for transition piece to achieve the same NOx reduction at the higher firing temperature. Fig.3 shows the configuration of this new combustor. By eliminating the transition cooling air, virtually all the combustion air is introduced into the primary zone of the combustor thus maintaining the flame temperature at nearly the same level as that of the M501F / M701F turbine. Therefore, NOx levels are similar to the M501F / M701F level (see Fig.4 and Fig.5).

Table 1 Performance of M701 Series Gas Turbine (ISO, LNG base)

Type	M701D	M701F	M701G2
First Unit Operating Year	1981	1992	2002
Gas Turbine Output (MW)	144	270	334
Gas Turbine Efficiency (% LHV)	34.8	38.2	39.5
Intake Flow Rate (kg/s)	441	651	737
Exhaust Gas Temperature (°C)	542	586	587
Pressure Ratio	14	17	21
Compressor Stage Number	19	17	14
Turbine Stage Number	4	4	4
Combined Output (MW) (1 on 1)	213	398	484
Combined Efficiency (LHV)	51.6	57.3	over 58

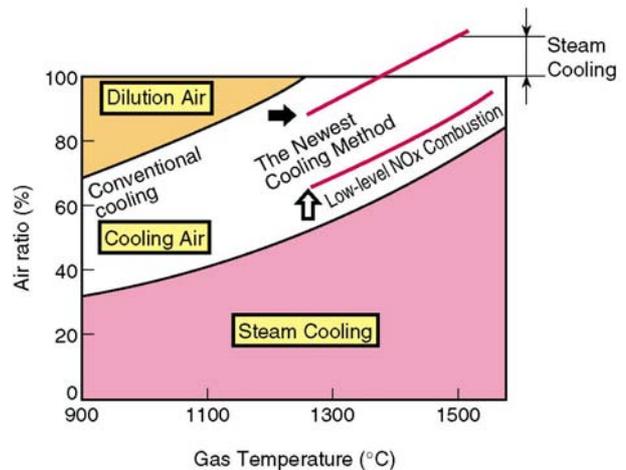


Fig.2 Combustion Air

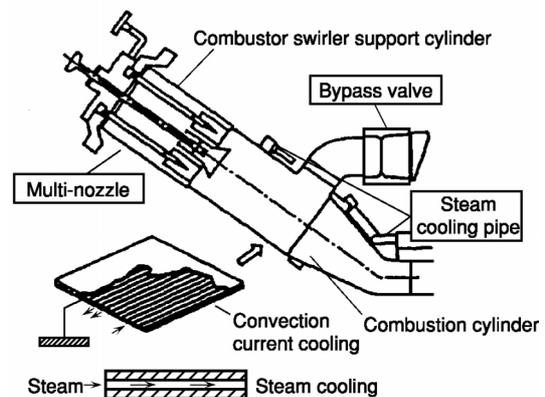


Fig.3 Structure of G series Gas Turbine Combustor

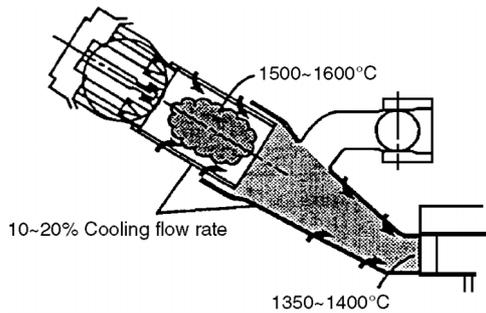


Fig.4 M701F Gas Turbine Combustor

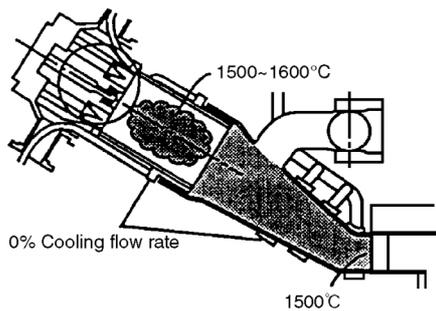


Fig.5 M701G2 Gas Turbine Combustor

Turbine

Mitsubishi scaling philosophy uses the same turbine airfoils for rows 1 and 2 for 50Hz and 60Hz applications (i.e. the same respective blade and vane geometries between the M501G and the M701G gas turbine). Improvements in aerodynamic airfoil shapes were achieved using fully three-dimensional viscous Euler analysis. This approach assures that the turbine has the highest practical aerodynamic efficiency, with the least cooling flow usage. There are 15 percent fewer airfoils compared to the M701F. The first two turbine blade rows are unshrouded. The third and fourth rows of blades are shrouded as on the M701F.

No changes were made in the turbine gas path materials. Table 2 also shows that those materials are also used in the M701F gas turbines. The first turbine stationary row consists of 40 precision-cast, single-vane segments of MGA2400, a nickel base super alloy that was developed by Mitsubishi. As in previous designs, the row 1 vanes are removable, without any cover lift, through access man ways. Inner shrouds are supported from the torque tube casing to limit flexural stresses and distortion, thus maintaining control of the critical row 1 vane angles. This method has been successfully used on M501F and M701F models as well. There are 22 precision-cast double vane segments of MGA2400 material in the second turbine stationary row. The third and fourth turbine stationary rows are precision-cast vane segments with 18 three-vane and 14 four-vane segments, respectively.

The rotating blades are precision cast of MGA1400 for all rows. Row 1 and row 2 blades are directionally solidified (i.e. DS). All rows utilize long blade root extensions or transitions in order to minimize the three-dimensional stress concentration factors that results when load is transferred between cross sections of different size and shape. The blade roots are the same geometric multiple serration type used on past designs with four serrations used on the first two rows and five serrations used on the last two stages.

Each row of vane segments is supported in a separate inner casing (blade ring) that is keyed and supported to permit radial and axial thermal response independent of possible external cylinder distortions. Blade ring distortion in the M701G2 turbine is further minimized by use of segmented isolation rings that support the vane segments and also ring segments over the rotor blades to form a thermal barrier between the flow path and the blade ring. As in all past designs, the interstage seal housings are uniquely supported from the inner shrouds of rows 2, 3 and 4 vane segments by radial keys that permit the thermal response of the seal housings to be independent of the more rapid thermal response of the vane segments.

The row 1 vane cooling is provided with impingement convection and film cooling. The film cooling holes are fan shaped and both the airfoil and shrouds will be coated with a ceramic thermal barrier coating. The row 1 vane cooling design is shown in Fig.6. This highly effective configuration utilizes state-of-the-art concepts with three impingement inserts in combination with an array of film cooling holes and a trailing edge pin fin system.

Film cooling is used at the leading edge as well as at selected pressure and suction side locations. This limits vane wall thermal gradients and external surface temperatures.

Particular attention is paid to the inner and outer shrouds because of the relatively flat temperature profile from the dry low NOx combustor. Cooling of shrouds is provided with impingement plates and film cooling as well as convection cooling via drilled holes.

Blade and vane cooling flows have been kept to a minimum while maintaining similar metal surface temperatures as in the case of the M701F. These advanced cooling schemes are developed through heat transfer model tests and cooled turbine hot cascade tests. Those were also verified through a high

Table 2 Materials for Turbine Vanes and Rotors

		M701F	M701G2
Vaness	Stage 1	MGA2400CC	MGA2400CC
	Stage 2	MGA2400CC	MGA2400CC
	Stage 3	MGA2400CC	MGA2400CC
	Stage 4	X-45	MGA2400CC
Rotors	Stage 1	MGA1400DS	MGA1400DS
	Stage 2	MGA1400CC	MGA1400DS
	Stage 3	MGA1400CC	MGA1400CC
	Stage 4	MGA1400CC	MGA1400CC

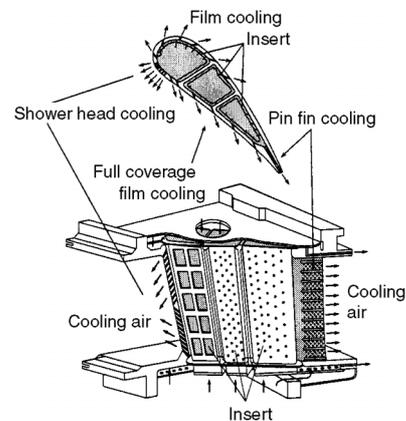


Fig.6 M701G2 Row 1 Vane

temperature demonstration unit by testing scaled-down turbine airfoils at actual operating temperature. Figure 7 shows the film cooling test in a low speed cascade to measure the film cooling effectiveness around the airfoil. Figure 8 shows the test of serpentine cooling passage with turbulence promoter to measure the heat transfer characteristics under rotating

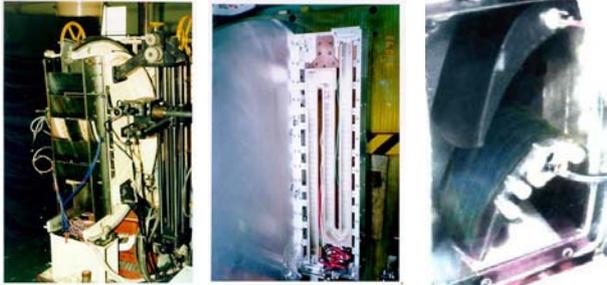


Fig.7 Measuring of film cooling efficiency Fig.8 Serpentine flow path heat transfer measuring test Fig.9 Measuring test for the heat transfer of the airfoil section.

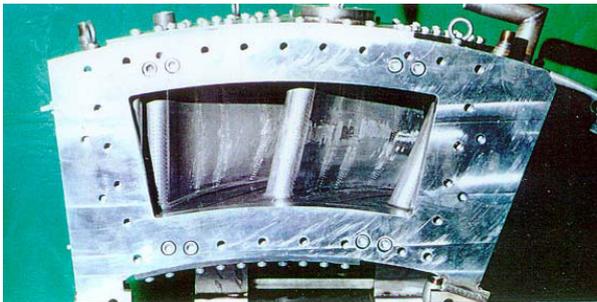


Fig.10 High Temperature Cascade Test of Row 1 vane

conditions. Figure 9 shows the airfoil heat transfer measurements using a liquid crystal. Figure 10 shows the hot cascade test section. This cascade test allows measurement of airfoil cooling performance under actual firing conditions.

The structure and the characteristic of the advanced blade ring with steam cooling technology are shown in Fig.12. By means of steam, the blade ring is enlarged during start-up. During the rated load, the steam, which temperature is lower than that of the sounding of the blade ring, cools the blade ring, establishing the suitable tip clearance for Row 1 and 2 blade.

Cooling Air System

Cooling circuits for the M701G2 turbine section displayed in Fig.11 are similar to those used on the M501F and M701F. They consist of a rotor cooling circuit and four stationary cooling circuits. Rotor cooling air is provided by compressor discharge air extracted from the combustor shell. This air is externally cooled and filtered before returning to the torque tube casing for the seal air supply and for cooling of the turbine discs as well as the first, second, and third stage turbine rotor blades. This cooled, filtered air provides a blanket of cooling air below the hot blade path gaseous layer. Also, filtering eliminates potential materials that could block the cooling passages in the rotating blades.

Compressor discharge air is directly used to cool the row 1 vane, while the bleed air also cools the stage 2, 3 and 4 vane segments and rotor disks and interstage seal flow, and stage 2 and 3 ring segments. Closed-loop steam is used for cooling turbine blade rings, and for cooling the combustor transition piece. This steam is supplied from the Heat Recovery Steam Generator, and subsequently returned to it after cooling.

The stationary vanes and rotating blades or the first two turbine stages are coated with thermal barrier coating. Compressor diaphragms are also coated to improve aerodynamic performance and corrosion protection. For some environments, the compressor blades are coated for added corrosion protection.

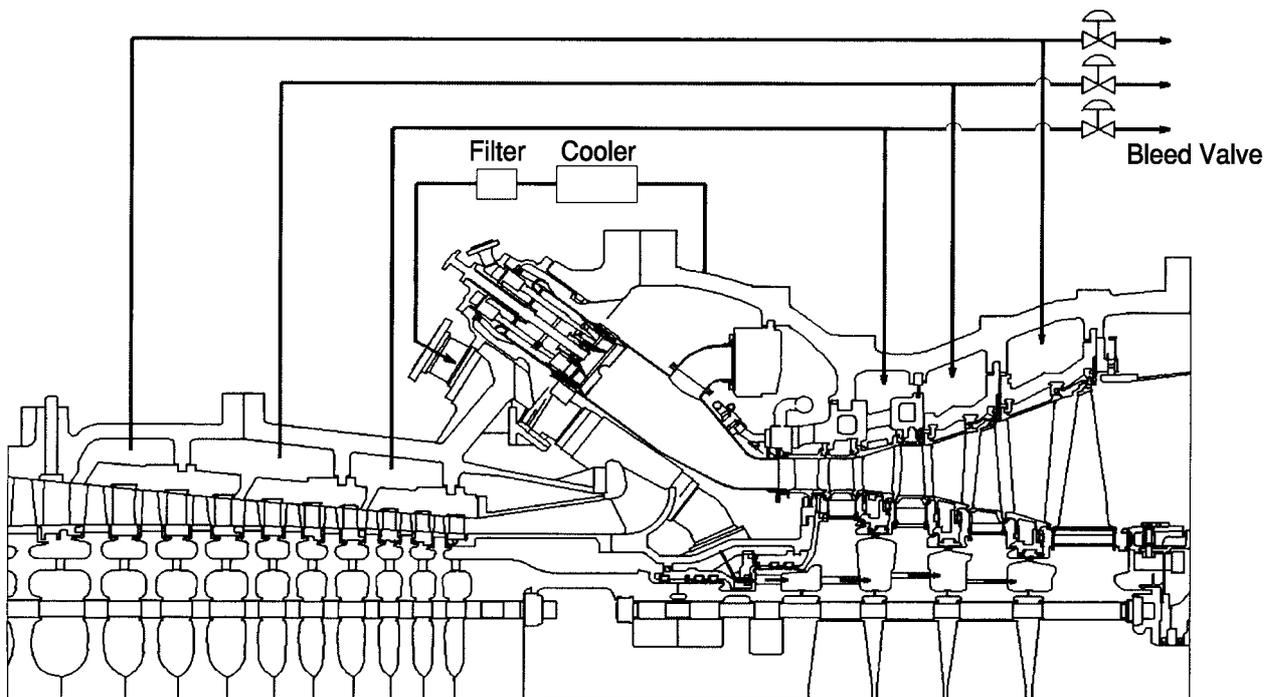


Fig.11 M701G2 Cooling Air System

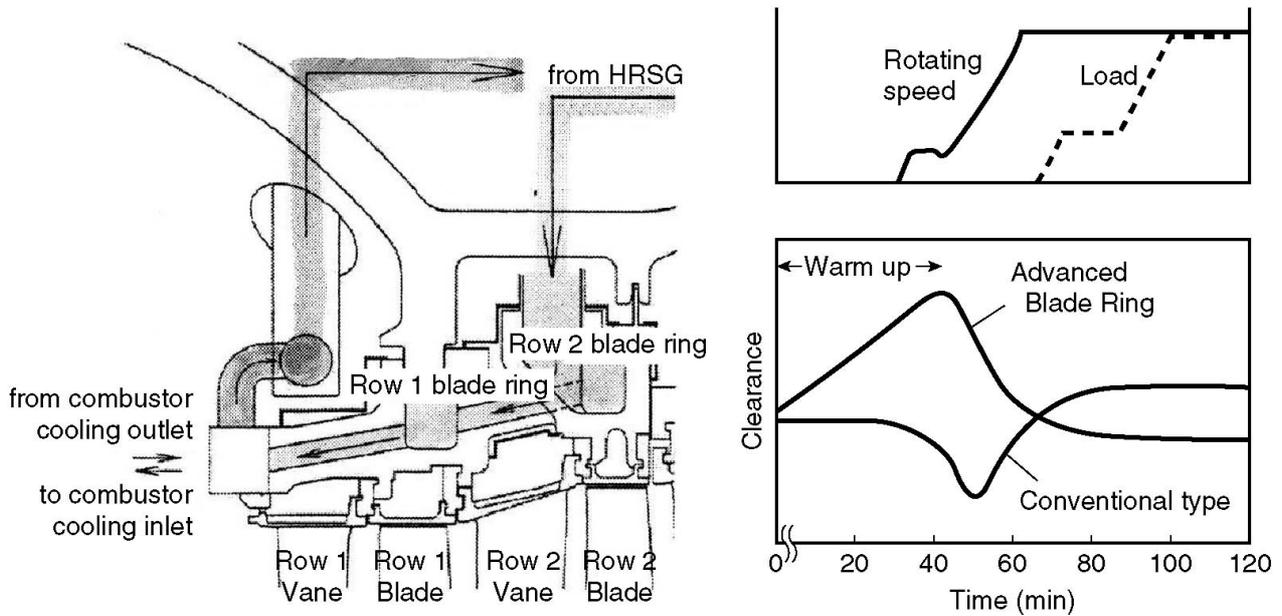


Fig.12 Advanced Blade Ring structure and characteristic

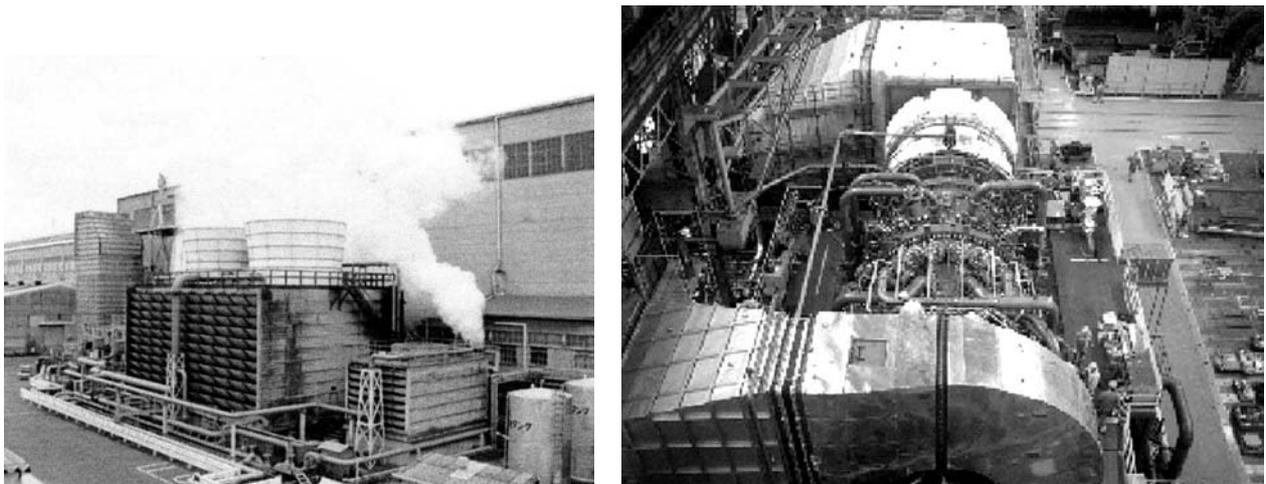


Fig.13 In-house Shop Load Test of M701G2

Turbine Stage 1 & 2 Advanced Blade Ring

To optimize the tip clearance of turbine blade, advanced steam-cooled blade ring is adopted to Stage 1 and 2. This blade ring follows the same design philosophy as the active clearance control used for aircraft engines. G series gas turbines, as mentioned earlier, employ the steam cooled system for combustor cooling. The active clearance control of M701G2 gas turbine is conducted by using this steam.

Structure and tip clearance characteristics of the advanced steam cooled blade ring are shown in Fig 12. In this scheme, the blade ring is warmed with steam during start-up, and the blade ring is enlarged to keep a sufficient clearance. During the rated load operation, the appreciate clearance is set by cooling the blade ring.

In-house shop Load Test

The shop load test was done to confirm the performance and

reliability of M701G2 at MHI Takasago Machinery & Works in April and May 2002.

The in-house test conditions are shown in Fig 13, and over 1800 specific measurement instrumentation were installed as shown in Fig 14.

The test verified that the scale-design compressor of M501H has a good performance, reliability and start-up characteristics. Fig 15 shows the measured vibration stress of the compressor vanes and blade. The vibration stress of the blades was taken by the non-contact laser motion measurement instrumentation (optic fiber sensor), and that of the vanes were measured by distortion gauge. It was verified that the result was well below the allowable.

Also, the performance and reliability of the entire gas turbine was tested, and the Rotor vibration characteristics were verified to be good as shown in Fig 16.

(A) Performance

- 1 Intake Air Flow Rate
- 2 Inlet Air Temperature / Pressure
- 3 Exhaust Gas Temperature / Pressure
- 4 Fuel Flow Rate
- 5 GT Output
- 6 Compressor Surge Margin
- Compressor Efficiency (pressure temperature)
- 7 Turbine Efficiency (pressure temperature)

(B) Metal Temperature

- 8 Combustor
- 9 Turbine #1,2 advanced Blade Ring
- 10 Turbine Stage 1 & 2 Vanes
- 11 Bearing
- 12 Casing
- 13 Blade Ring, Vane Support Ring
- 14 Exhaust Chamber

(C) Stress / Vibration

- 15 Compressor Rotor (BVM)
- 16 Compressor Vane (guage)
- 17 Combustion Vibration
- 18 Rotor Vibration
- 19 Casing Vibration
- 20 Rotor Casing Vibration

(D) Others

- 21 Cooling Air System
- 22 Thrust
- 23 NOx, CO, UHC
- 24 Expansion Difference
- 25 Noise
- 26 Lubricant

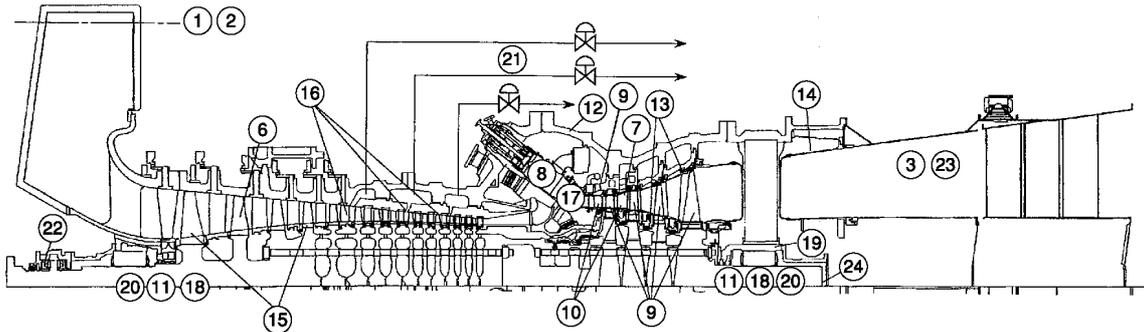


Fig.14 M701G2 In-house Shop load Test Specific Items

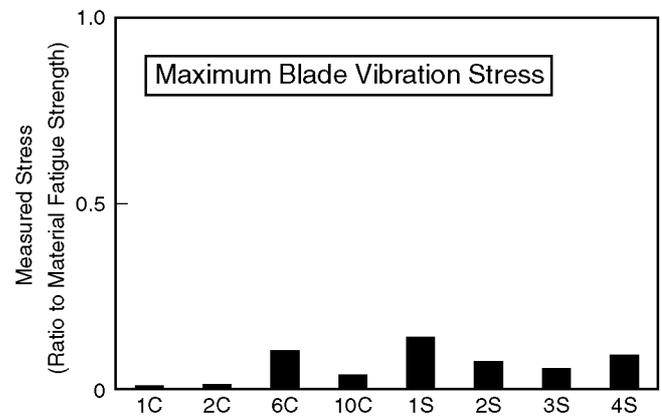
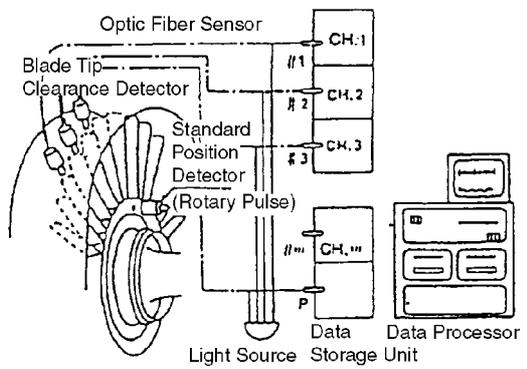
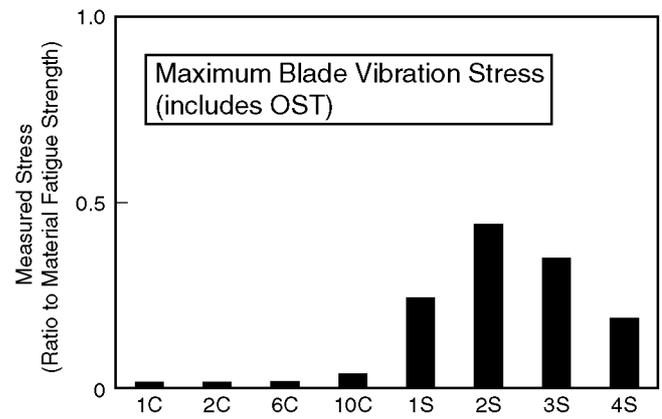
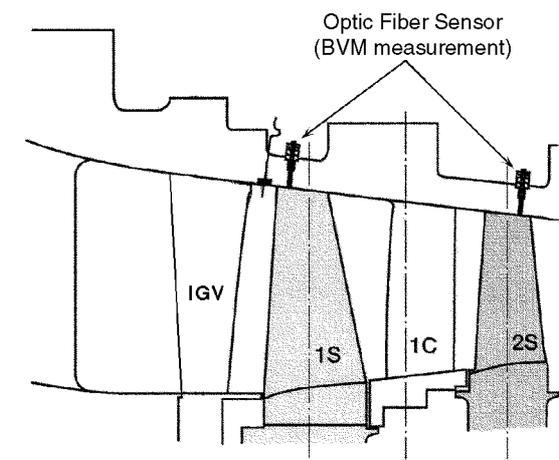


Fig.15 Combustor Blade / Vane Vibration Stress Measurement result

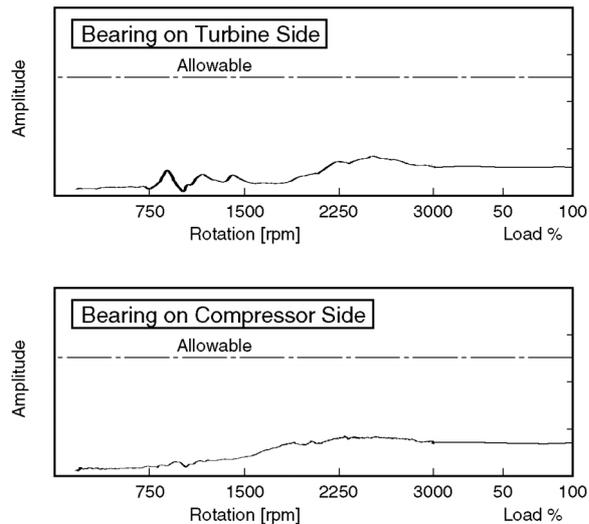


Fig.16 Rotor Vibration

Conclusion

It is possible to improve further the over-all thermal efficiency of combined cycle plant that utilizes high temperature/high efficiency gas turbine. Mitsubishi Heavy Industries developed the M701G2 type gas turbine, with a 1500°C class high temperature, and world's largest capacity, highest efficiency gas turbine.

In-house shop load test was implemented in April 2002; the result of specific instrumentation covering over 1800 items verifies that the mechanical reliability and performance is good as expected.

It is anticipated that M701G2 Gas Turbine will contribute to the world environment as the main unit of high efficiency combined cycle power plant.

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