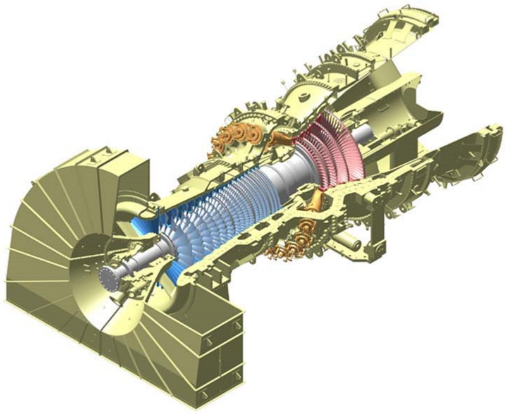
Technology Application to MHPS Large Frame F series Gas Turbine



JUNICHIRO MASADA*1 MASANORI YURI*2

TOSHISHIGE AI*2 KAZUMASA TAKATA*3

TATSUYA IWASAKI*4

The development of gas turbines, which Mitsubishi Hitachi Power Systems, Ltd. (MHPS) has continued to pursue, contributes to society in terms of global environmental conservation and a stable energy supply. MHPS leverages its abundant gas turbine operation experience and takes advantage of its extensive advanced technology research on "Component Technology Development for 1,700°C Class Ultra-High-Temperature Gas Turbines" for the national project. The company has been participating in this project since 2004. Recent years' achievements include the demonstration of a gas turbine combined cycle (GTCC) efficiency in excess of 62% by increasing the turbine inlet temperature to the 1,600°C class in the M501J in 2011. Up to the present time, 25 units of the "J" have been brought into commercial operation, achieving a cumulative operational time of more than 470,000 hours. The Latest M701F incorporates "J" gas turbine technologies, already applied to actual equipment, for efficiency improvement. It also applies air-cooled combustor technologies successfully validated in the GAC, for increased flexibility. The 1st unit started commercial operation in 2015 and currently 4 units have accumulated more than 52,000 actual operating hours collectively. On the other hand, MHPS offers an upgrade program for existing F-series gas turbines that will result in higher performance and reliability by applying proven technology developed for new frames, in parallel with the development of new frames. This paper presents the features of the latest M701F gas turbine and the upgrades for existing F-series gas turbines.

1. Introduction

Gas turbine combined cycle (GTCC) power generation represents the most efficient and cleanest way to generate power using fossil fuels. It also features a high load following capability and as a result has a high affinity with renewable energy.

An increase of gas turbine temperature constitutes an important element to improve the efficiency of GTCC power generation. In 1984 Mitsubishi Heavy Industries, Ltd. (MHI) developed the M701D gas turbine featuring an inlet temperature of 1,100°C. Since that time, the development of technologies that improve the capacity, efficiency and reliability of GTCC plants was actively promoted at MHI. This led to the development of the 1350°C class M501F in 1989 and the 1,500°C class M501G in 1997. MHI joined the "Component Technology Development for 1,700 °C class Ultra-High-Temperature Gas Turbines" national project in 2004, targeting further improvement of gas turbine efficiency. Efforts were made to develop the advanced technologies needed to realize high temperature and high efficiency. Using some of the achievements, the 1,600°C class turbine

*1 Deputy Head of Turbomachinery Headquarters, Mitsubishi Hitachi Power Systems, Ltd.
*2 Deputy Director, Large Frame Gas Turbine Engineering Department, Gas Turbine Technology & Products Integration Division, Turbomachinery Headquarters, Mitsubishi Hitachi Power Systems, Ltd.
*3 Manager, Large Frame Gas Turbine Engineering Department, Gas Turbine Technology & Products Integration Division, Turbomachinery Headquarters, Mitsubishi Hitachi Power Systems, Ltd.
*4 Large Frame Gas Turbine Engineering Department, Gas Turbine Technology & Products Integration Division, Turbomachinery Headquarters, Mitsubishi Hitachi Power Systems, Ltd.

inlet temperature M501J was developed and validated at the power generation facility for validation (T Point) in MHPS Takasago Machinery Works in 2011(**Figure 1**, **Figure 2**, and **Figure 3**).

In parallel with the development of new frames, MHI/MHPS continuously improves existing gas turbines by applying the technologies developed for new frames. The performance and reliability of the 50Hz F units were improved sequentially after completing the development of the M701F gas turbine in 1992. The M701F (2009) benefitted from the introduction of new technologies validated by the "G" gas turbine, which features a 1,500°C class turbine inlet temperature. The development of the latest M701F gas turbine has been completed, which is based on the M701F (2009) basic structure and incorporates "J" gas turbine technologies. The first unit started commercial operation in 2015 and currently 4 units have accumulated more than 52,000 actual operating hours collectively. In addition to the latest M701F, we are also improving the performance and reliability of the existing F-series through upgrades by applying blades and vanes that reduce cooling air.

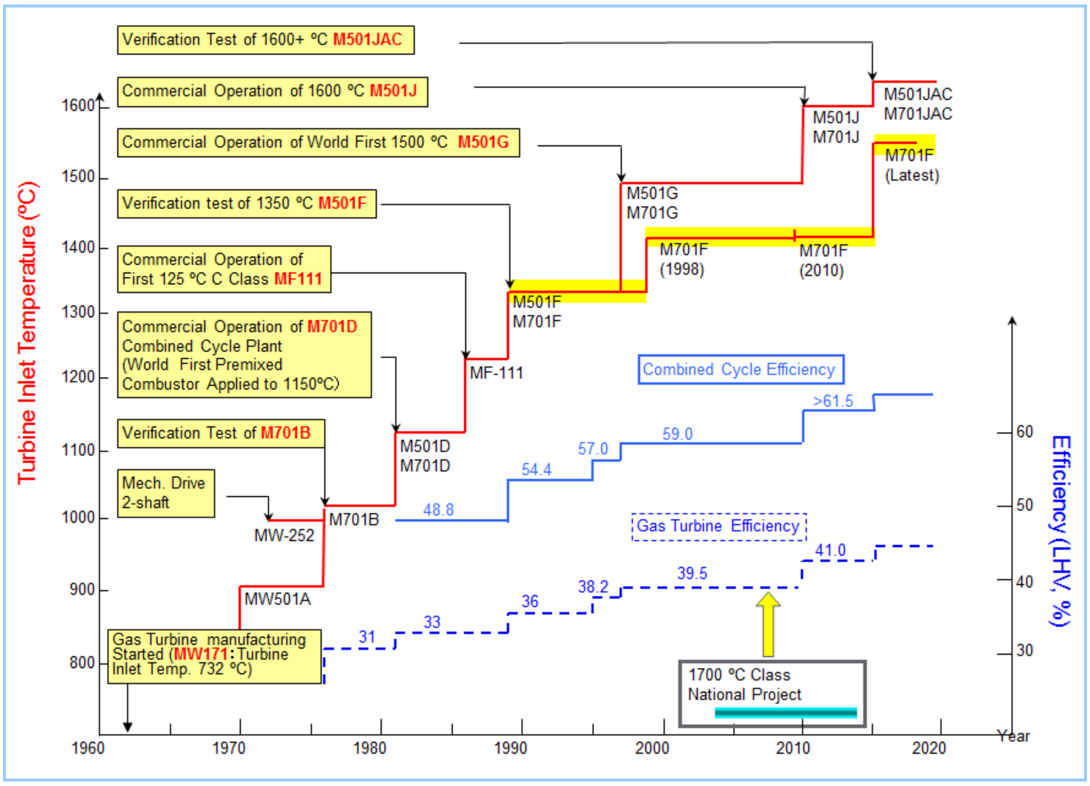


Figure 1 Evolution of MHI/MHP's Large frame gas turbine

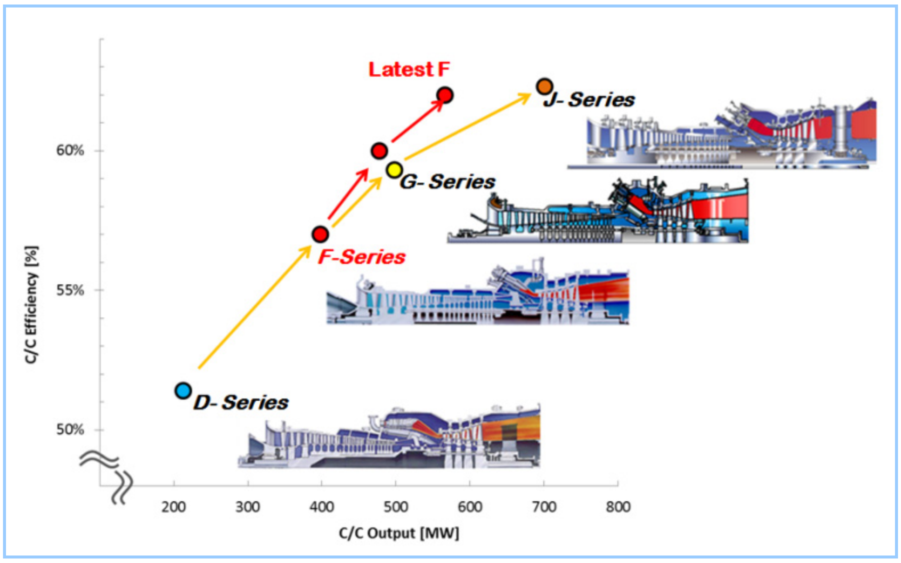


Figure 2 Development history of MHI/MHPS Large Frame Gas Turbines

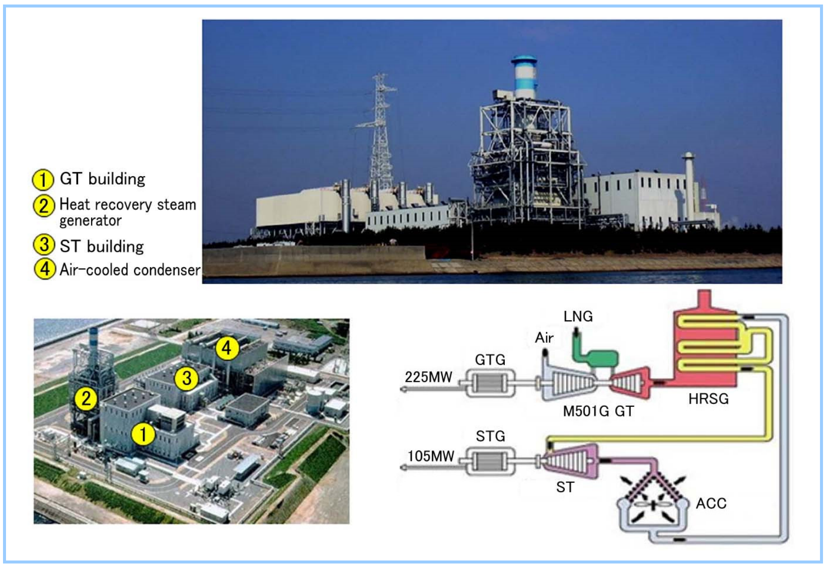


Figure 3 Power generation facility for validation (T Point)

2. Features of the latest M701F Gas Turbine

The latest M701F gas turbine is structurally based on its prior model, M701F, but incorporates advanced component technologies applied to other frames. The compressor is based on the M701F (2009), but incorporates CDA (Control Diffusion Airfoil) profiles for efficiency improvement. The combustor incorporates a Dry Low NOx combustion system, which is the proven air-cooling technology verified in the “GAC”. The aerodynamics and cooling technologies developed for the 1,600°C class “J” are incorporated in the turbine. **Figure 4** and **Figure 5** show the technologies introduced to the latest M701F gas turbine and their characteristics.

Resulting in MHI/MHPS’s continuous efforts to introduce new technologies, the output of the original M701F gas turbine (234MW) was increased to 385 MW for the latest M701F, which has approximately 1.5 times higher generation capacity, while improving the combined efficiency by more than 12% over the past 20 years, contributing substantially to a reduction in fuel consumption and CO_2 emissions. **Table 1** shows the main features including the gas turbine and GTCC performance of the F-series gas turbines to date.

The latest M701F gas turbine was inspected as scheduled after over 10,000 hours of commercial operation. Detailed inspection has been carried out on all parts including fuel nozzles, combustor baskets and transition pieces, turbine blades and vanes and accessory components, and has been found to be in sound condition without cracks or TBC loss.

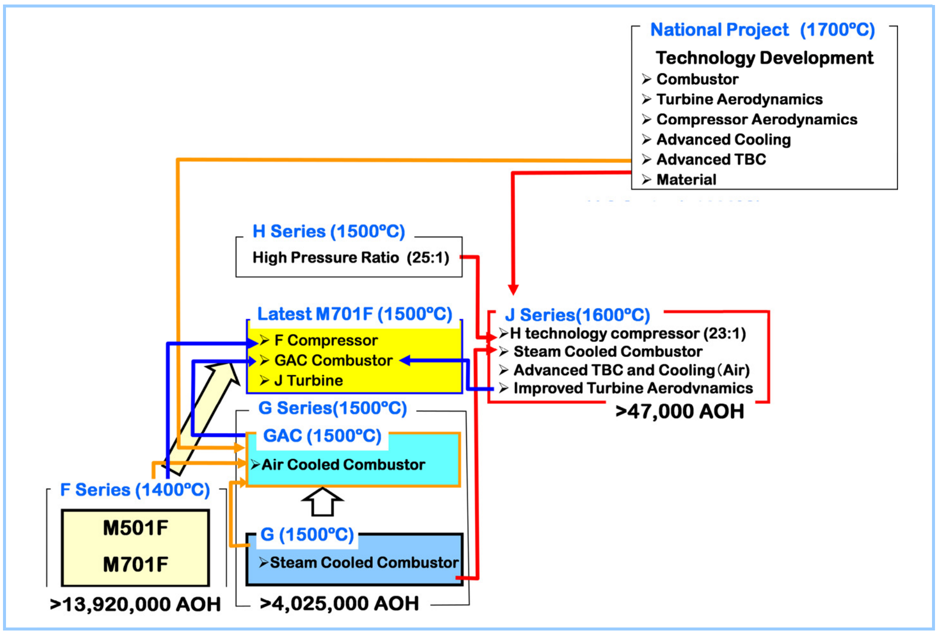


Figure 4 Deployment of component technologies for each type of frame

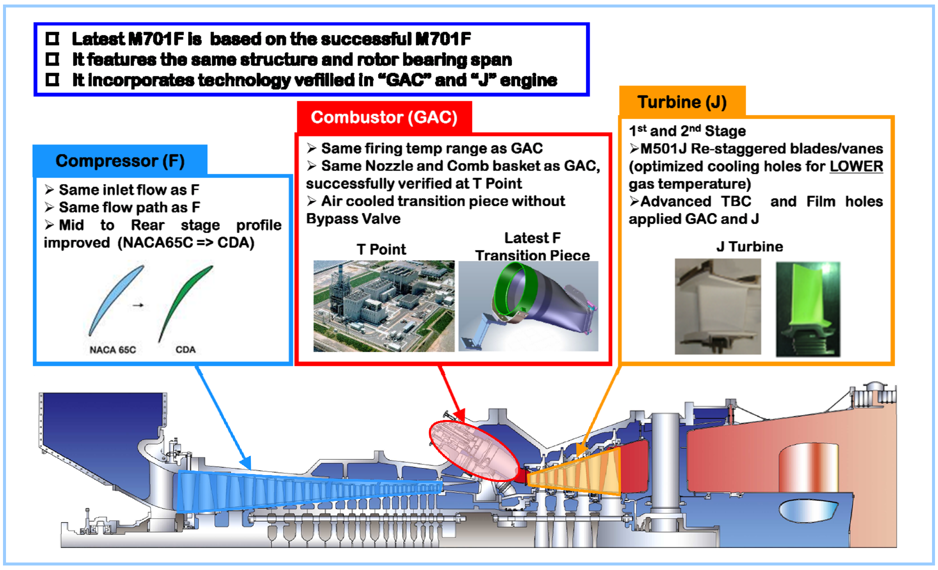


Figure 5 Features of LATEST M701F gas turbine

Table 1 Gas turbine performance (ISO, standard condition) and major specifications

Frame (Year of initial unit delivery)	M701F (1992)	M701F (2009)	M701F (2014)
Rotating Speed	3000 rpm	3000 rpm	3000 rpm
Gas turbine output	234 MW	312 MW	385 MW
GTCC output	334 MW	465 MW	566 MW
GTCC efficiency (LHV)	54.4%	59.5%	62%
Compressor	17 stages		
Combustor	Air-cooled type 20 cans		
Turbine	1st to 3rd stages Air cooling 4th stage Not cooled		

2.1 Compressor

The compressor flow path of the Latest M701F is the same as its prior model, M701F (2009), and maintains the same compressor inlet flow rate. The profile of the compressor blades and vanes on the front six stages are the same as M701F (2009). The blade tip speed and aerodynamics characteristics on the first stage are also the same. The blades and vanes profile on the middle and rear stages were changed from the conventional NACA to CDA blades to improve efficiency (**Figure 6**). The CDA blade features optimized velocity distribution on the blade surface. This type of blade was applied to the "G", "H" and "J" gas turbines developed after the introduction of original F series gas turbine.

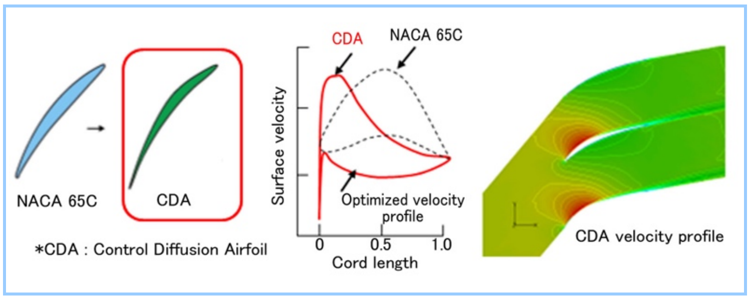


Figure 6 Features of CDA blades

2.2 Combustor

The combustor technologies that have been applied to the "GAC" were incorporated in the latest M701F. The nozzle and the swirler that exhibited stable combustion performance in the "GAC" and afterwards in the 1,600°C class "J" gas turbine (**Figure 7**) are applied to the latest M701F. The transition piece of the J is cooled with steam supplied from outside the gas turbine while an air cooled gas turbine, like the latest M701F does not link the steam cycle with the gas turbine providing improved flexibility. This is the same concept applied to the "GAC". Following the successful experience of the GAC and J, the combustor by-pass mechanism is not installed in the latest F in order to improve reliability by simplifying the structure.

The combustor bypass mechanism controls Fuel/Air ratio of the combustor basket by adjusting the amount of the air flow into the combustor basket. When the gas turbine was at partial load condition, where the flame temperature in the combustion area is lower, the combustor bypass valve was opened for decreasing the air into combustor basket and increasing the flame temperature at combustion area. In case of eliminating the combustor bypass mechanism such as the latest F combustor, the F/A of the combustion area is adjusted by changing the number of main nozzles used for combustion.

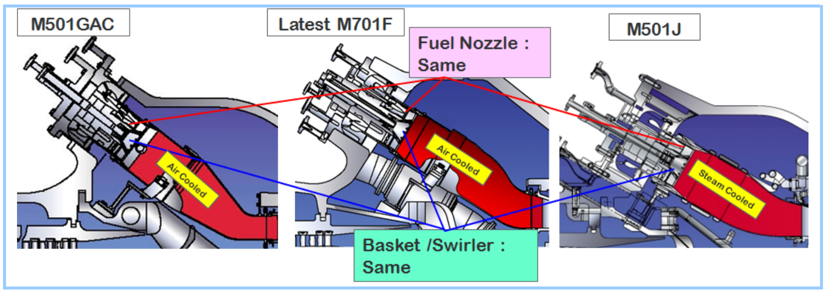


Figure 7 Combustion parts among GAC, J and Latest M701F

2.3 Turbine

The turbine blades and vanes are exposed to high-temperature and high-pressure combustion gas from the combustor. They are cooled by compressor discharge air or bleed air from the intermediate stage of the compressor to keep the metal temperature of the blades and vanes within the limit value to ensure the designed service life. However, cooling air becomes a loss in the turbine section and therefore it is key to improve performance to reduce the amount of cooling air applied without affecting the reliability of the components.

Cooling technologies have advanced in line with the increase in turbine inlet temperature (**Figure 8**). The "J" featuring a 1,600°C class turbine inlet temperature incorporates the advanced TBC technologies and high-efficiency film cooling technologies developed by the "Component Technology Development for 1,700 °C class Ultra-High-Temperature Gas Turbines" national project that MHPS has been involved with since 2004. The latest M701F also adopts these technologies.

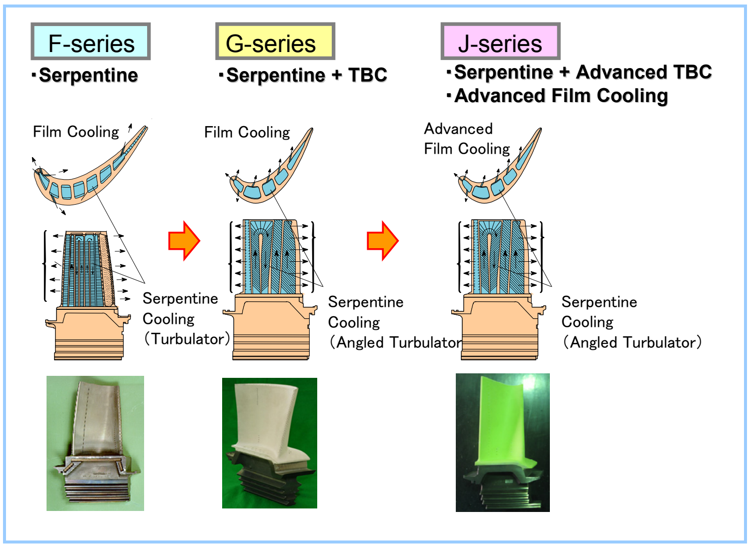


Figure 8 Turbine blade technologies

The advanced TBC (Thermal Barrier Coating) is applied to the blades and vanes of the three front stages, and a higher durability is important in addition to a higher heat shield effect. The durability of the advanced TBC was confirmed by laser thermal cycle test (**Figure 9**) before application to actual blades.

High-efficiency film cooling (**Figure 10**) is incorporated for cooling the surface of the turbine blades. This method is more effective than conventional film cooling. In film cooling, the gas path on the blade surface is covered by cooled air to reduce the gas temperature on the blade surface. The outlet shape of the cooling holes on the film was optimized to cover a wider area of the blade surface with the same film air rate, optimizing the total cooling air amount.

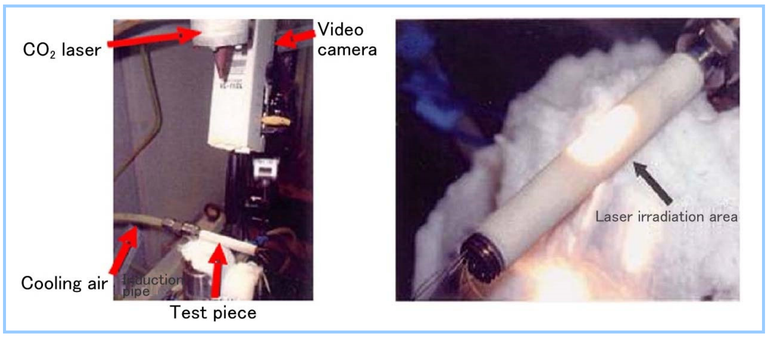


Figure 9 Laser thermal cycle test of advanced TBC

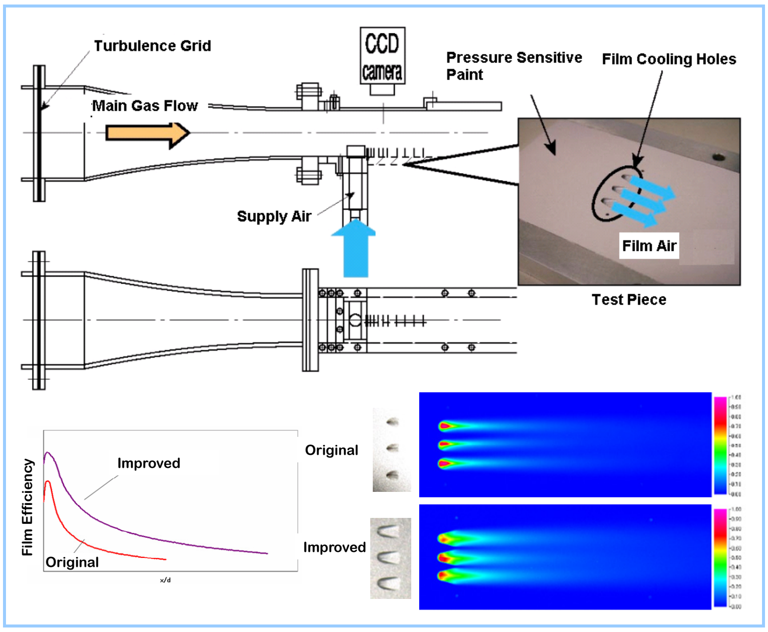


Figure 10 Film cooling effectiveness

3. Upgrade program for existing F-series gas turbine

"J" and "GAC" technologies developed and presented based on Japanese national projects can be applied not only to the latest M701F, but also to existing F-series gas turbines. MHPS provides upgrade menus to improve the efficiency, output and reliability of existing F-series gas turbines by applying the advanced technology of "J" and "GAC" (**Figure 11**). By upgrading the compressor and turbine of an existing F-series, it is possible to improve the gas turbine output by about 10%.

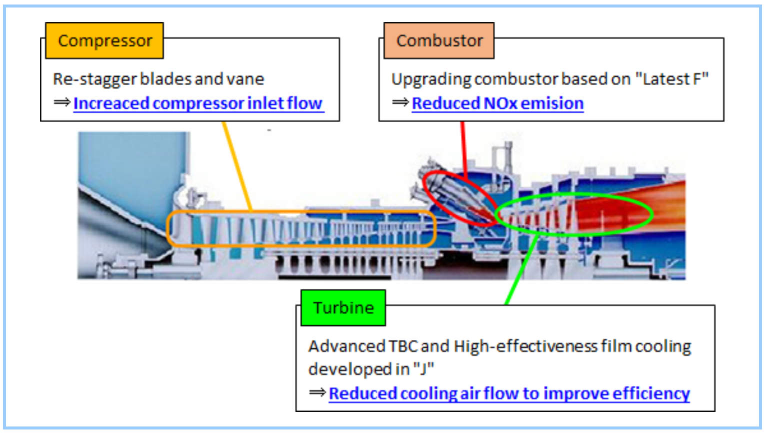


Figure 11 Upgrade Program for F-Series Gas Turbine

3.1 Compressor Upgrade

Increasing the inflow flow rate is one of reliable countermeasures for increasing the output of the gas turbine. In case of upgrading the gas turbine, it is important to minimize replacement parts from the viewpoint of securing reliability and cost optimization, so that the flow path dimensions of the compressor are not changed in order to minimize the change range. Compressor blades and vanes were redesigned by applying the advanced technology of "J" in order to achieve both an increase in inlet flow rate and reliability while maintaining compressor flow path dimensions as design constraints (**Figure 12** and **Figure 13**).

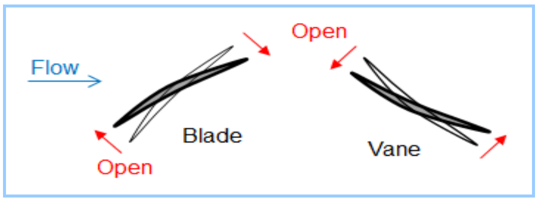


Figure 12 Open Re-stagger Compressor blades and vanes

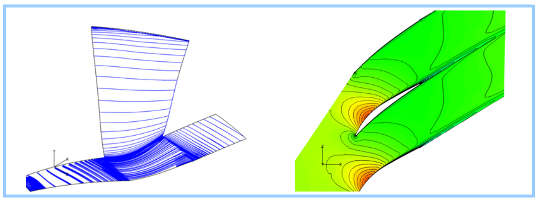


Figure 13 Streamline and Velocity counter of Upgrade compressor

3.2 Turbine Upgrade

The reduction of turbine cooling air improves gas turbine performance. Increasing combustion gas flow caused by the reduction of turbine cooling air improves the power and performance of the gas turbine.

The turbine upgrade program improves performance by applying the latest cooling air reduction technology to turbine blades and vanes.

(1) Advanced TBC

Developed to maximizes the heat shield effect, while also increasing coating thickness.

(2) Advanced Film Cooling

Cooling air covers a wider range of the airfoil surface.

In addition to the above technologies, the following advanced technologies that have been proven in the abundant achievements of the F-series and the G-series can be applied to upgrading turbines.

(3) Optimized Film Cooling Hole Arrangement

Optimized arrangement by considering the shroud end wall stream line.

(4) Airfoil wall Thickness Optimization

Airfoil wall thickness was reduced for surface metal temperature reduction. The mechanical structure was optimized through FEA.

(5) Modified Cooling Scheme

In order to improve cooling efficiency, the latest internal cooling method was applied to improve the heat transfer turbulence promotion effect of cooling air and to optimize the impingement cooling.

(6) High Strength Alloy

Mitsubishi Gas Turbine Alloy (MGA) is one of the MHPS original super alloy. The latest developed material has excellent weldability for repair and outstanding resistance to creep, fatigue and oxidation.

The turbine upgrade program should not only improve performance by applying the latest technology, but also ensure reliability. The upgrade program is sophisticated technology with appropriate technical knowledge based on the experience of the OEM fleet. The development process that feeds back the experiences of the J series and the latest F fleet operation to the design enhances the reliability of the upgrade program.

3.3 Combustor Upgrade

The NOx emissions from conventional type of F series Gas Turbine is reduced by applying the upgrade combustor developed based on the “Latest F” combustor technologies (**Figure 14** and **Figure 15**). The “Original F” combustor is equipped with conventional fuel nozzle and combustor air bypass mechanism. While Combustor air bypass mechanism is useful to control Fuel/Air ratio for keeping combustion stability, a lot of leaks of the air are disadvantageous from a point of the NOx reduction.

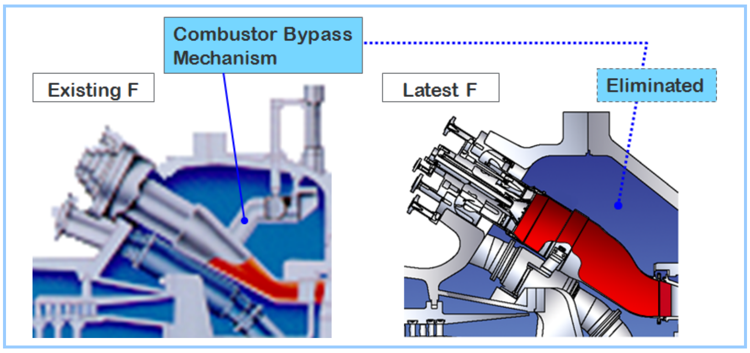


Figure 14 Combustor comparing original F and upgrading

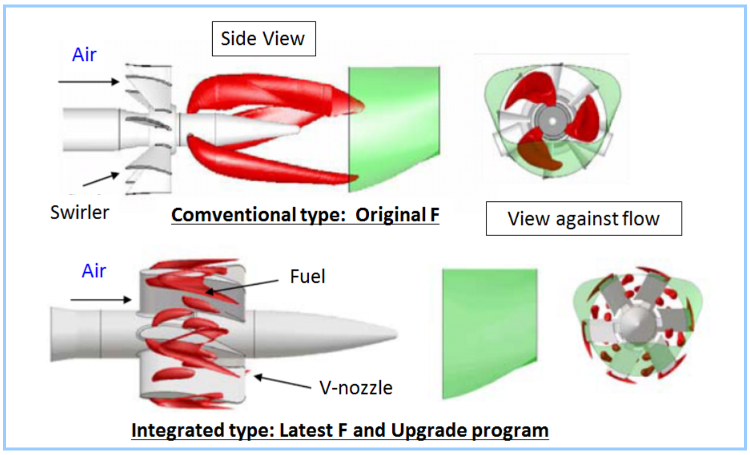


Figure 15 Improvement of fuel nozzle

The upgrading combustor has decreased air leakage to reduce the NOx emissions. The "Latest F" combustor is based on "GAC" combustor that has eliminated the combustor air by-pass mechanism to reduce the NOx emissions by decreasing air leakage. In addition, the upgrading combustor applied Advanced Thicker TBC which was developed in "M501J" to the combustor basket and transition pieces. This TBC reduces the cooling air flow of the combustor and thereby reduces NOx emissions by lowering the base flame temperature.

NOx reduction technology is also applied to fuel nozzle for the upgrading combustor. The improvement of the combustor nozzle surrounding for the purpose of more homogeneous fuel-air mixing lowers the peak flame temperature in the combustion area and thereby limits NOx emission concentrations.

The NOx emissions are decreased to twothirds from half by applying the upgrade combustor based on the Latest F combustor to the "Original F series gas turbine".

4. Conclusion

To date, our F-series gas turbine has been continuously improved since bringing the M501F gas turbine into practical use in 1989 by utilizing the technologies for the G-series and the J-series, which were developed thereafter. The latest M701F, to which the J-series technologies are applied, started commercial operation in 2015, and has successfully accumulated 52,000 hours of operation collectively to date. At the same time, we also developed upgrade options that apply these technologies to the existing F-series, and are applying them to actual units one after another.

By developing these technologies and achievements, we will continue to improve the performance and reliability of the latest and existing F-series gas turbines and respond to expectations from customers and society, in parallel with advancing the development of next-generation frames in the future.

References

1. Masada et al., Development of the High Efficiency and Flexible Gas Turbine M701F5 by Applying "J" Class Gas Turbine Technologies, Mitsubishi Heavy Industries Technical Review Vol. 51 No. 1 (2014)