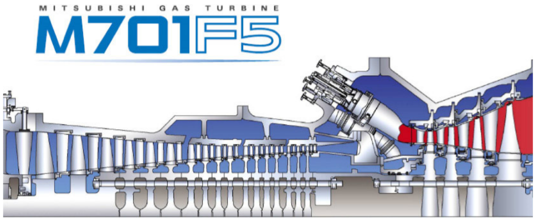
Development of the High Efficiency and Flexible Gas Turbine M701F5 by Applying "J" Class Gas Turbine Technologies



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The development of gas turbines, which Mitsubishi Heavy Industries, Ltd. (MHI) has continued to pursue, contributes to society in terms of global environmental conservation and a stable energy supply. MHI leverages its abundant gas turbine operation experience and takes advantage of its extensive advanced technologies 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 includes the demonstration of a gas turbine combined cycle (GTCC) efficiency in excess of 61.5% by increasing the turbine inlet temperature to the 1,600°C class in the M501J in 2011(1)(2)(3). The M701F5 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 delivery of the initial unit is scheduled for 2014. This paper explains the features and development status of M701F5 gas turbine.

1. Introduction

Gas turbine combined cycle (GTCC) power generation represent 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. Global demand for GTCC power generation equipment has been increasing following the development of shale gas fields and the increase in the supply of natural gas.

An increase of gas turbine temperature constitutes an important element to improve the efficiency of GTCC power generation. In 1984 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 inlet temperature M501J was developed and validated in 2011 (**Figure 1**, **Figure 2**). This frame features a GTCC thermal efficiency in excess of 61.5%. The 50 Hz M701J, a scale design of the 60 Hz M501J, has also been developed, with the first unit scheduled for delivery in 2014.

In parallel with the development of new frames, MHI 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 to the "F2", "F3" and "F4" after completing the development of the M701F gas turbine in 1992. The "F4" 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 a state-of the-art gas turbine M701F5 has been completed, which is based on the "F4" basic structure and incorporates "J" gas turbine technologies (**Figure 3**). The first unit is now under manufacturing and will be delivered in 2014.

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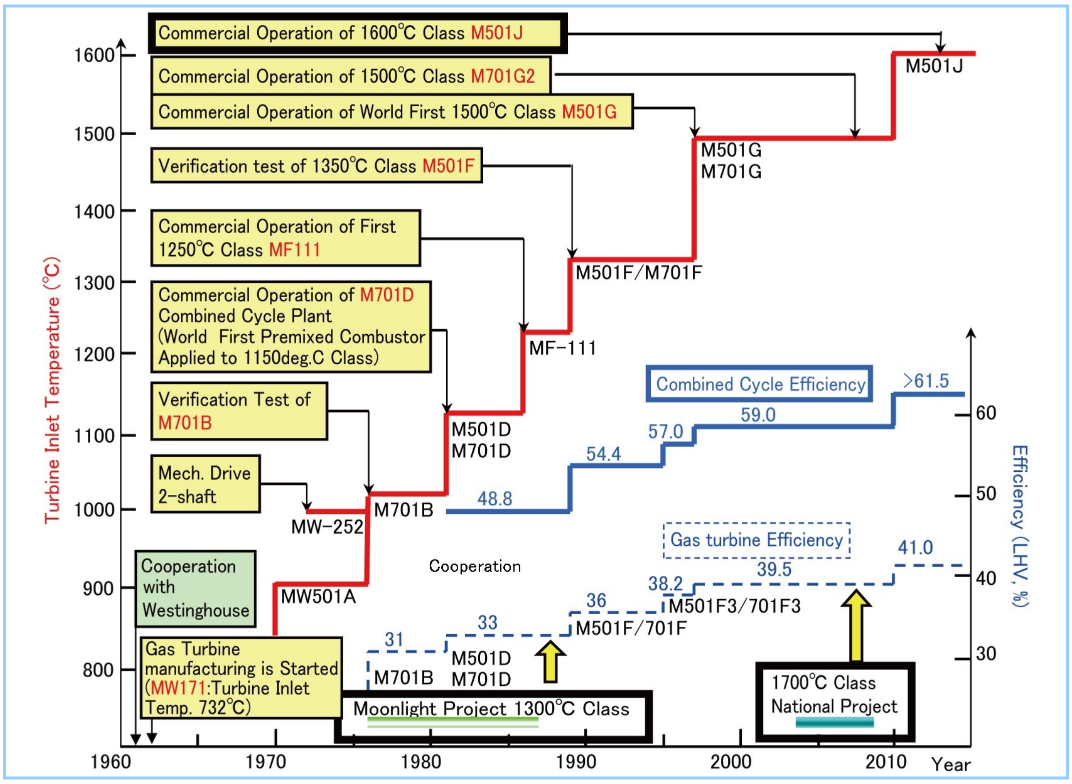

Figure 1 History of improvements in temperature and efficiency of MHI gas turbines

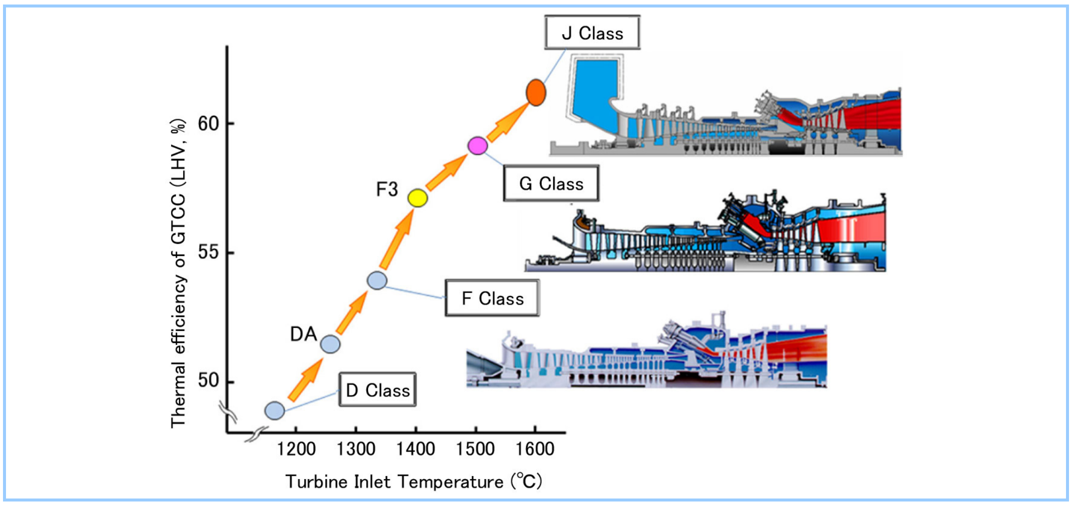

Figure 2 Development history of Mitsubishi gas turbines

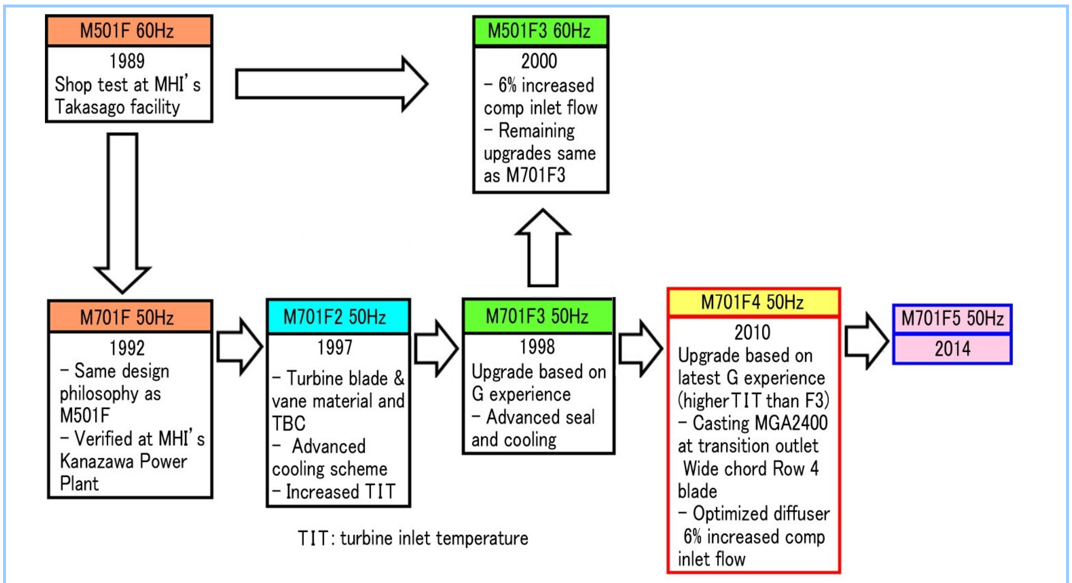

Figure 3 Evolution of F-class gas turbine

Resulting in MHI continuous efforts to introduce new technologies, the output of the M701F gas turbine (234MW) was increased to 359 MW for the M701F5, 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 M701F, F4 and F5.

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

Frame	M701F	M701F4	M701F5
Year of initial unit delivery	1992	2009	2014
Rotating Speed	3000 rpm	3000 rpm	3000 rpm
Gas turbine output	234 MW	312 MW	359 MW
GTCC output	334 MW	465 MW	525 MW
GTCC efficiency (LHV)	54.4%	59.5%	61% min.
Compressor	17 stages		
Combustor	Air-cooled type 20 cans		
Turbine	1st to 3rd stages Air cooling 4th stage Not cooled		

2. Features of the M701F5 Gas Turbine

The M701F5 gas turbine is structurally based on its predecessor the M701F4, but incorporates advanced component technologies applied to other frames, following MHI design philosophy to ensure reliability and improve efficiency at the same time. The compressor is based on the M701F4, 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**[(4)] show the technologies introduced to the "F5" gas turbine and their characteristics.

2.1 Basic Structure

Large gas turbines must supply electric power constantly; therefore Reliability and flexibility are essential. The M701F5 gas turbine is structurally based on the "F" gas turbine and has the same bearing span of its predecessor. The "F" adopts a highly-reliable basic structure that has been validated by many years of operation. The features of the basic structure are described below.

(1) 2-bearing support system
(2) Horizontal split casing which ensures easy disassembly and inspection
(3) Cold-end drive to reduce the influence of thermal expansion
(4) Axial exhaust appropriate for the layout of the combined cycle power plant arrangement
(5) Tangential strut structure that reduces the thermal expansion induced vertical displacement of the bearing core during operation
(6) Bolt-joined rotor that transmits torque perfectly by torque pin in the compressor side and the curvic coupling in the turbine
(7) Side entry compressor and turbine rotating blades, which allows in-situ blade replacement without lifting the rotor
(8) Blade ring structure that prevents deformation and keeps tip clearance at the minimum level
(9) Multi-can combustor featuring easy maintenance

A total of 197 "F" class units have been delivered. The fleet has accumulated 9,097,000 actual operating hours with 86,800 start and stop as of September 2013, indicating abundant operation experience. The data is shown in **Table 2**. The 60 Hz units were delivered in western Japan, East Asia and North and Central America, while the 50 Hz units were delivered to eastern Japan, Southeast Asia, Europe and South America. They are contributing to the stable supply of power in each region.

Table 2 Operating Experience of "F" Class Gas turbine (as of September 2013)

	M501F series (60Hz)			M701F series (50Hz)			TOTAL
	In Operation	New Order	Sub-total	In Operation	New Order	Sub-total	
F	20	0	20	14	0	14	34
F2				2	0	2	2
F3	47	6	53	72	3	75	128
F4				16	13	29	29
F5				0	4	4	4
Total	67	6	73	104	20	124	197

F Feet Total: 197 Units (171 In Operation, 26 New Order)
- Accumulated Experience: 9,097,000 hours / 86,800 starts

F3 Feet Total: 128 Units (119 In Operation, 9 New Order)
- Accumulated Experience: 5,571,000 hours / 51,700 starts
- Lead M501F3 unit: 99,400 hours / 2,400 starts
- Lead M701F3 unit: 104,000 hours / 1,300 starts

F4 Feet Total: 29 Units (16 In Operation, 13 New Order)
- Accumulated Experience: 129,000 hours / 1,500 starts
- Lead M701F4 unit: 22,500 hours / 180 starts

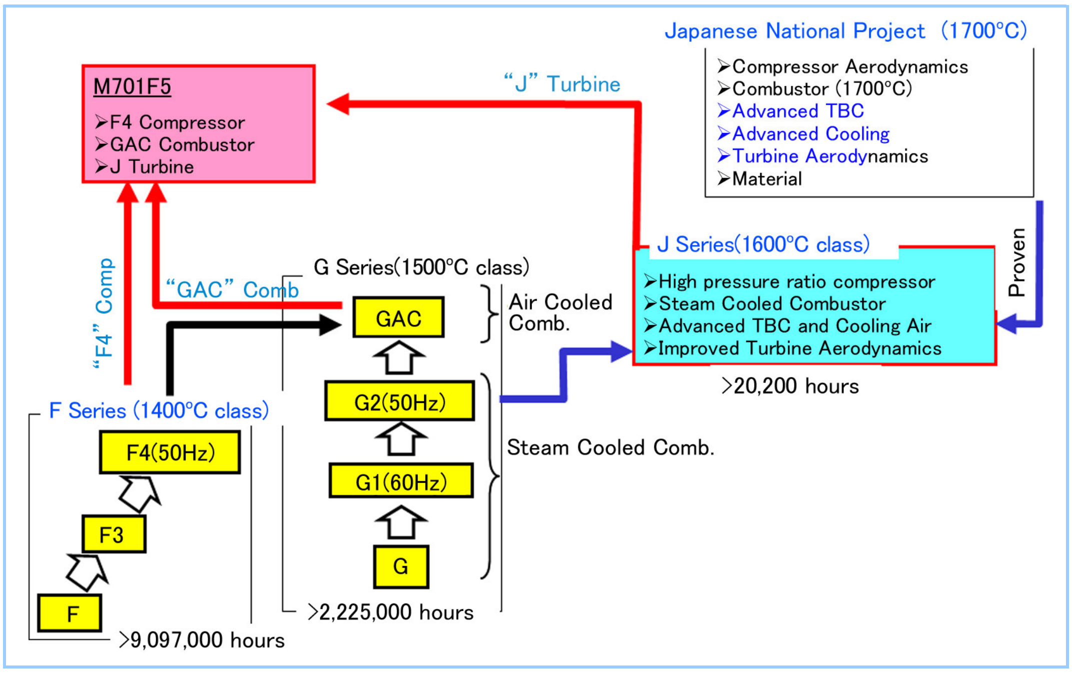

Figure 4 Relationship between other frames and M701F5

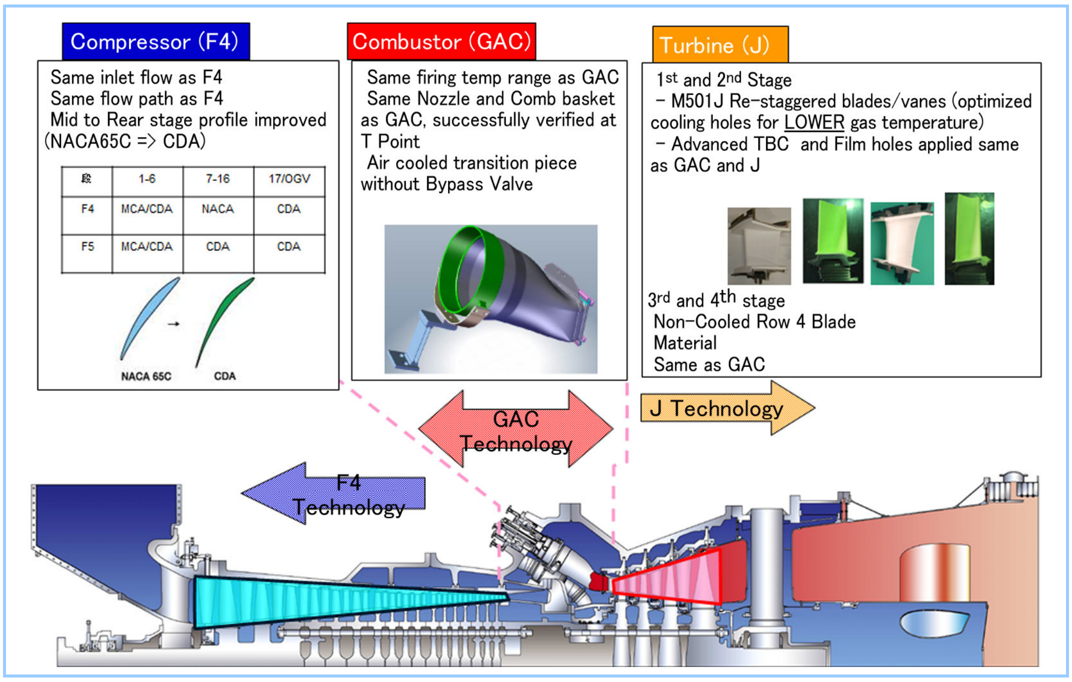

Figure 5 Features of M701F5 gas turbine

2.2 Compressor

The aerodynamic stability of the compressor is highly affected by the first compressor stage. If designed properly, it can prevent or diminish the effect of rotating stall and other instabilities during startup. The F4 compressor has demonstrated stable behavior and low sensitivity to instabilities during start up. Therefore, the same flow path has been applied to the M701F5. In other words, the same blades as "F4" are used for the front 6 stages of "F5" and the inlet air flow rate and the blade tip speed on the first stage are also the same. The same resilience to start-up instabilities is expected based on the operation experience of the "F4". 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. MHI incorporated this type of blade in the "G", "H" and "J" gas turbines, which were developed after the F introduction. This CDA blade is also used on the front stage of the F4 units and they have accumulated more than 120,000 hours. The CDA blades are proven technology widely used in MHI recent developments including the "F4". For this reason, the "F5" compressor also incorporates this technology levering the excellent results obtained in the "F4" providing reliability while improving efficiency.

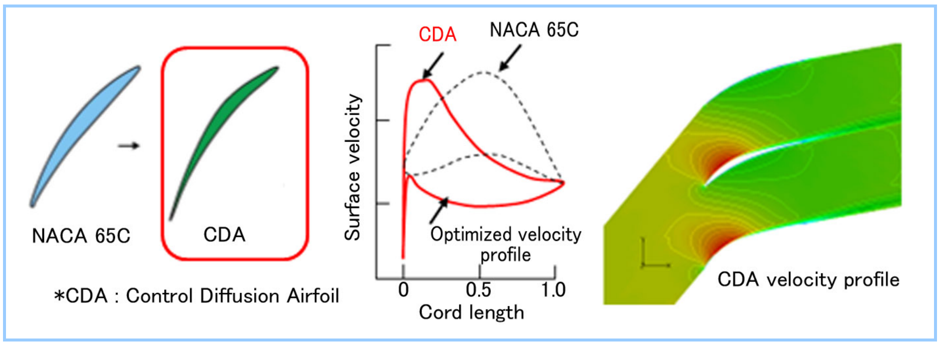

Figure 6 Comparison between NACA and CDA profiles

2.3 Combustor

The combustor technologies that have been applied to the "GAC" were incorporated in the "F5". 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 F5. The transition piece of the J is cooled with steam supplied from outside the gas turbine while an air cooled gas turbine, like the F5 does not link the steam cycle with the gas turbine providing improved flexibility. This is the same concept applied to the "GAC".

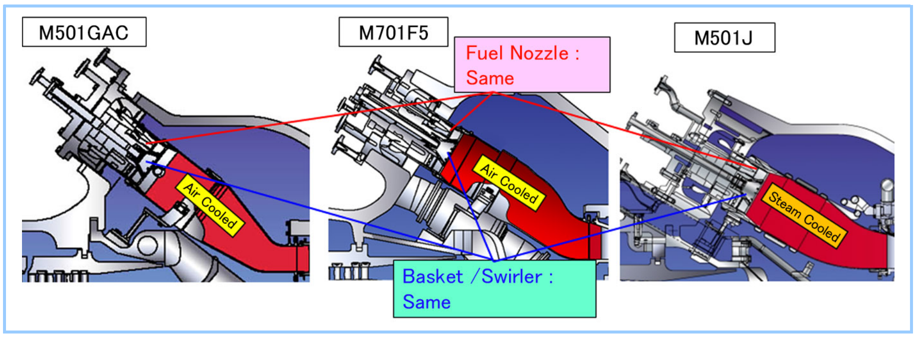

Figure 7 Common combustors parts among "GAC", "J" and "F5"

Because the air used for the combustor cooling is mixed with combustion gas in the combustor, the flame temperature inside the combustor increases against the turbine inlet temperature (average gas temperature at the 1st stage stationary vane). The flame temperature affects NOx and combustion stability, therefore, the air-cooled "F5" flame temperature was selected at the lower level than that of steam-cooled "J". Consequently, the turbine inlet temperature of the "F5" is lower than that of the "J", and the "F5" cooling design of turbine parts was optimized in response to the results.

Following the successful experience of the GAC and J, the combustor by-pass has been eliminated in the F5 to increase reliability. In addition, MGA (Mitsubishi Gas Turbine Alloy) material originally developed for the turbine stationary vanes is applied to a precision casting area at the outlet of the transition piece, which is subjected to severe thermal stress.

A high pressure combustion test using the "F5" combustor was completed in MHI Takasago Works test facility. This test confirmed that the NOx level is far below the target value of NOx 15 ppm (15% O_2 conversion) and the combustion stability and metal temperature of the combustor basket and the transition piece, which affect its reliability, are within allowable limit with sufficient margin.

2.4 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 MHI has been involved with since 2004.

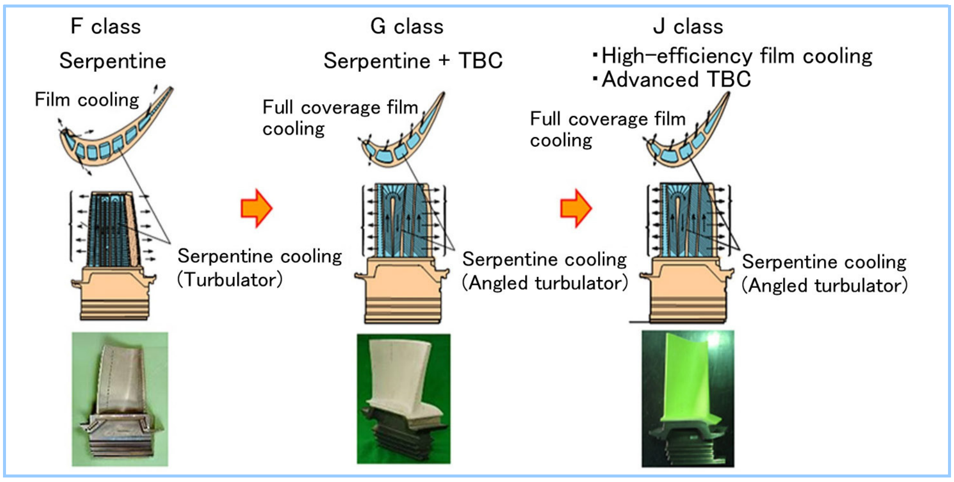

Figure 8 Turbine blade technologies for each frame

The "F5" and the "J" include a 4-stage turbine with TBC (Thermal Barrier Coating) applied to the blades and vanes of the three front stages. Heat input from high-temperature gas to turbine blades is reduced by the adoption of the advanced TBC, which features a higher heat shield effect and durability compared with conventional coating materials. This contributes to a reduction in the cooling air rate for the blade metal temperature at a level below the limit value. The durability of the advanced TBC was confirmed by laser thermal cycle test (**Figure 9**) before application to actual blades.

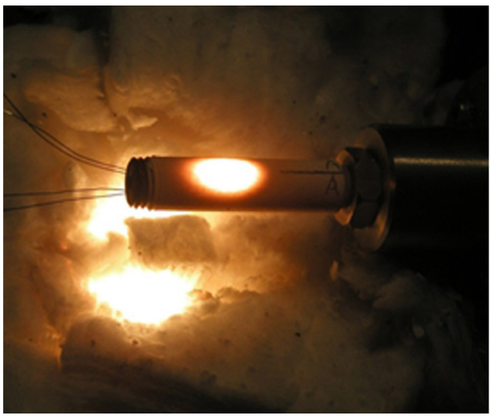

Figure 9 Laser thermal cycle test of advanced TBC

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.

The advanced TBC technologies and high-efficiency film cooling technologies were originally developed by the national project for 1,700°C class gas turbines and validated by the 1,600°C class "J" gas turbine. They were incorporated in "F5" gas turbine, resulting in improved reliability and performance at the same time.

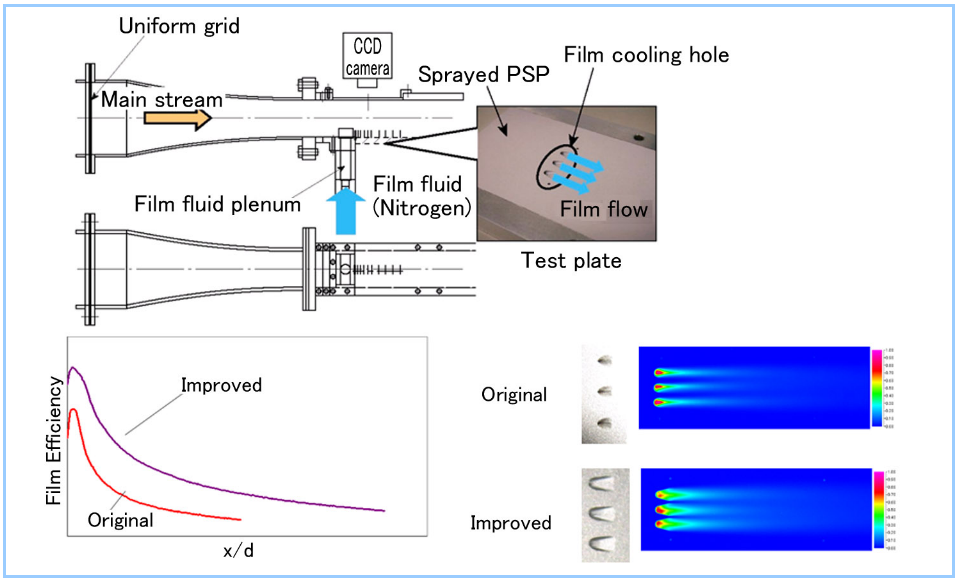

Figure 10　High-efficiency film cooling

3. "F5" Technologies Validated at T point

To develop gas turbines, MHI first validates each component technology at the research laboratory, followed by detailed designing and production of the actual engine. The products are validated at the power generation facility for demonstration (T point) at the final process of new technology validation. T point is a combined cycle power plant installed in the premises of MHI Takasago Works. This plant is equipped with a gas turbine, a steam turbine and a heat recovery steam generator (HRSG) (**Figure 11**), where the M501G started operation in January 1997 and the performance and reliability of "G" were verified.

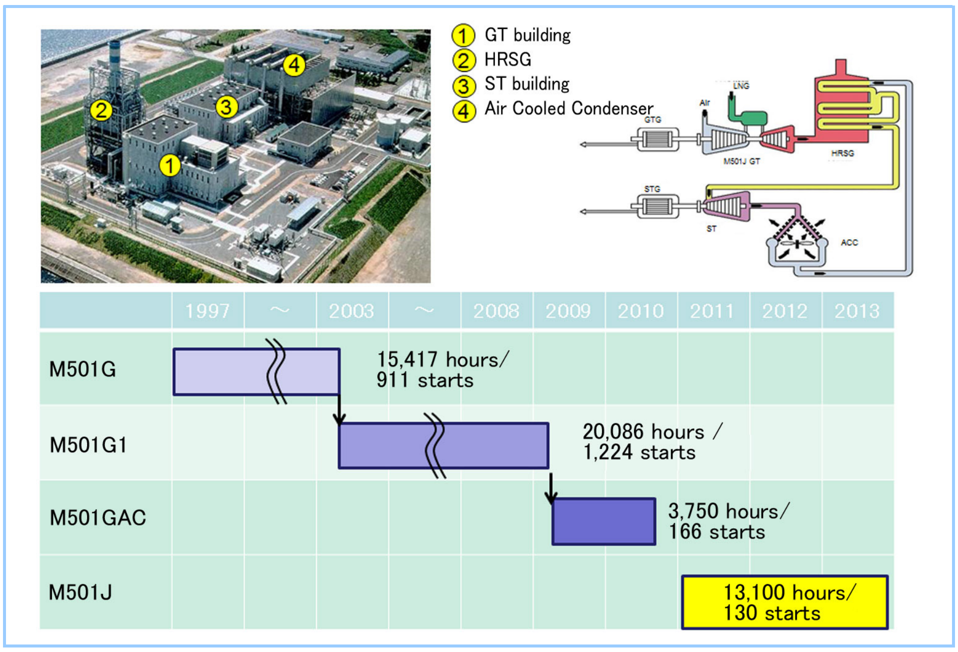

Figure 11　Power generation facility for validation (T point)

T point gas turbine was later upgraded to M501G1 and M501GAC to verify their functionality. In October 2010, T point was renovated for validation of the M501J with the 1600°C commissioning operation starting in February 2011. More than 2,300 temporary measurement sensors were equipped for this engine, confirming that its performance, mechanical characteristics and combustion stability satisfied the target values.

Figure 12 shows the metal temperature distribution of the row 1 stationary vane. The metal temperature at each location is well within the limit value, indicating that there are no problems in terms of reliability. The profile and platform metal temperature of row 1 rotation blade were measured with a pyrometer confirming satisfactory results. The metal temperature measurement results at the platform of row 1 rotating blade are shown in **Figure 13**.

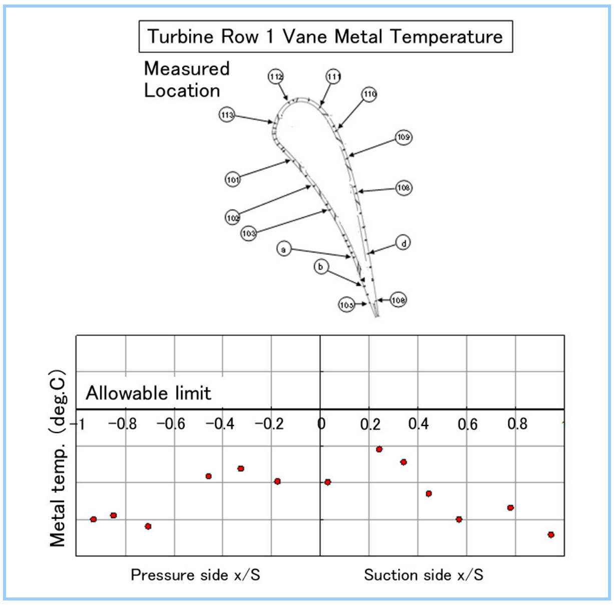

Figure 12 Metal temperature measurement results of row 1 stationary vane of M501J turbine

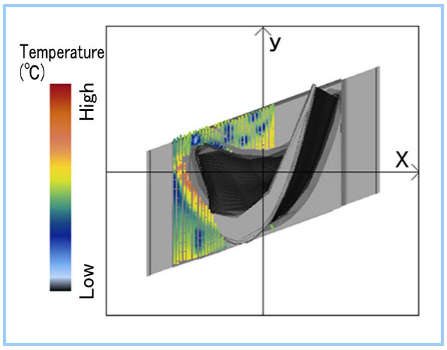

Figure 13 Metal temperature measurement results of row 1 rotating blade of M501J turbine

After completing the M501J commissioning in June 2011, the long-term reliability validation started and is still ongoing. As of the end of September 2013, the operating experience reached 13,100 hours and the 130 start and stop. **Figure 14** shows the results of inspections performed in March 2013. The results indicate that the parts after operation remain in good condition.

The lessons learnt from operation and inspections obtained at the T point have also been reflected in the M701F5. The air-cooled combustor technologies leverage the "GAC" successful experience and the turbine technologies for the "J". This contributes to the high performance and reliability of "F5" gas turbines.

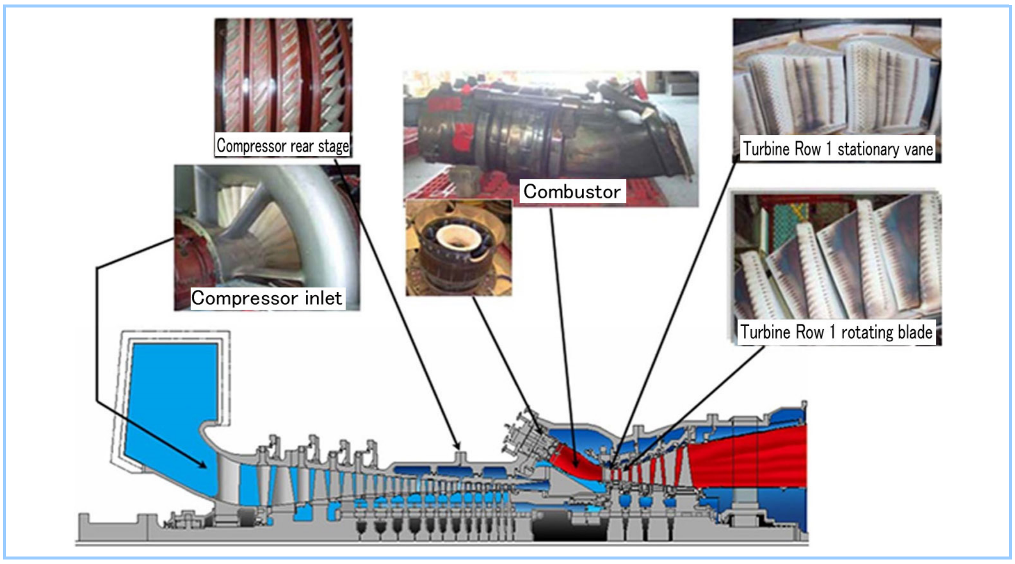

Figure 14 Inspection results of M501J at T point (March 2013: 10,548 hours/120times)

4. Conclusion

MHI has developed gas turbines based on abundant gas turbine operation experience and research for advanced technologies including a national project named "Component Technology Development for 1,700°C class Ultra-High-Temperature Gas Turbines." The development of the M701F5 incorporating turbine technologies validated by actual operation in the latest 1,600°C class M501J was successfully completed. The gas turbine components are currently being manufactured, with the delivery of the initial unit scheduled for 2014 and trial operations expected to start in fiscal 2015. Gas turbine combined cycle (GTCC) power generation features the highest level of efficiency among fossil fuels power generation while being environmentally friendly. Under these circumstances and with power sources increasingly diversified and scattered, the M701F5 gas turbine will contribute to the stable supply of electricity to the world in the future with high flexibility and high efficiency.

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