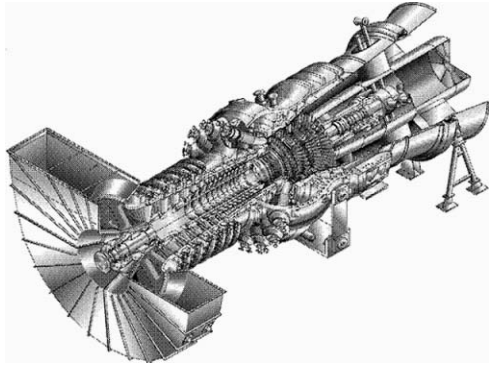


# Trial Operation Results of Steam Cooled M501H Type Gas Turbine



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The "H" series gas turbine is a high efficiency and high power output gas turbine. The total thermal efficiency is about 2% higher and the output power is about 10% greater than that of a G series gas turbine. The reason the "H" series gas turbine can achieve a higher efficiency and a larger output is that its high temperature turbine first- and second-stage vane/blade are cooled by steam supplied from the bottoming cycle, instead of conventionally used air. Accordingly, the amount of bleed air from the compressor can be reduced. In 1999, the first trial operation of the "H" series gas turbine was conducted in the in-house verification power generation facility installed at the Takasago Machinery Works of Mitsubishi Heavy Industries, Ltd. (MHI). A second trial operation run was subsequently completed successfully at the same facility in 2001. Consequently, MHI has completed development of this new gas turbine using the prototype of the "H" series gas turbine. This paper reports on the development of the "H" series gas turbine.

## 1. Introduction

MHI developed the 1150°C class large capacity gas turbine engines known as the M701D in 1981 and verified their high plant total thermal efficiency, reliability, and capability to protect against pollution at the No.3 Higashi Niigata Thermal Power station of the Tohoku Electric Power Company. In 1985, MHI started development of the 1350°C class "F" series gas turbine (M501F/M701F). Actual shop load tests were conducted on the first gas turbine of this series in 1989. Afterwards, MHI began development of the 1500°C class "G" series gas turbine in 1993. Trial operation tests of the M501G gas turbine for the 60Hz market were begun in February 1997 at the gas turbine combined cycle verification plant (hereafter referred to as the "T" point) installed at the Takasago Machinery Works. Long-term verification operational tests started in June 1997 at the same plant. On the other hand, commercial operation began on the M701G gas turbine for the 50Hz market at the Tohoku Electric Power Company's No. 4 Higashi Niigata Thermal Power station in July 1999.

These "D", "F", and "G" series large capacity, high efficiency gas turbines are the engines aimed at increasing plant output and improving plant efficiency by increasing the turbine inlet temperature, while maintaining the reliability of the equipment. On the basis of the extensive experience obtained through the development of these gas turbines, the "H" series gas turbine has been developed in order to increase the turbine capacity and efficiency even further.

An overview of the first trial operation in the de-

velopment of the "H" series gas turbine engine has already been reported on the January 2000 issue of the Mitsubishi Juko Giho Vol. 37 No. 1. Consequently, this report is intended to focus on an outline of the second trial operation (performed in 2001) in which the gas turbine reached the rated load, and the soundness and the reliability of the system were verified.

## 2. Outline of "H" series gas turbine

### 2.1 Schedule of development

The schedule of development of the "H" series gas turbine is shown in **Table 1**. Work on the development

**Table 1 Schedule of development**

	1996	1997	1998	1999	2000	2001
T-Point M501H		Design		Advanced Design		
		Manufacture		1st trial operation	Manufacture	2nd trial operation
Component test		Seal test				
		Steam cooling vane test				
		Model rotor test				
			Model compressor test			
				High temp. rotating verification test		
				High temp. cascade test		
				High press. combustion test		
					Advanced seal test	
						High-temp. full-speed full-scale rotating test

design was begun in 1996, and the first trial operation was performed at "T" point in February 1999. The component tests were repeated at that time in order to verify the performance of individual components. After that, further improvements to the design were added. This was followed by a second trial operation that was carried out from December 2000 through March 2001. Completion of these tests saw development work using the prototype finally coming to a close.

## 2.2 Feature of "H" series gas turbine

The turbine inlet temperature of the "H" series gas turbine is 2732°F (1500°C), equivalent to that of a "G" series engine. However, the "H" series turbine has one significant characteristic that distinguishes it from its earlier cousin. This is the adoption of steam-cooled vane/blade instead of the air-cooled vane/blade that are used in the G series gas turbines and the earlier models. In other words, a steam cooling system has been adopted for the first- and second-stage vane/blade in the "H" series gas turbine. **Fig. 1** shows the schematic flow diagram of the "T" point used in the trial operations. The high-pressure turbine outlet steam is sent to the H series gas turbine to cool them. The steam used to cool the vane and blade is then recovered and returned to the intermediate pressure steam turbine inlet.

The main advantages of the "H" series gas turbine can be summarized as follows.

- (1) It is possible to increase the inlet temperature in the first stage blade, because the reduction in gas temperature before and after cooling of the turbine first stage vane achieves about half that compared with that in air cooling.
- (2) Heat loss due to mixing with cooling air can be reduced. Also, vane/blade cooling steam supplied from the bottoming cycle is recovered to the bottoming cycle again after exchanging heat at the turbine airfoils, that is, energy is recovered, so that combined cycle thermal efficiency can be increased further.

As the amount of combustion gas increases in corresponding proportion to the decrease in the amount of cooling air, the work that can be done by the turbine increases, that is, gas turbine output increases. As a result, the "H" series gas turbine achieves a high efficiency and a high power output. Specifically, the total thermal efficiency is about 2% higher and the output power is about 10% higher than those of a "G" series gas turbine of the same basic construction.

The main features of the "H" series gas turbine are summarized below.

- (1) Steam for cooling the blades is supplied from the turbine side shaft end to the interior of the rotor and recovered from the same shaft end. In order to

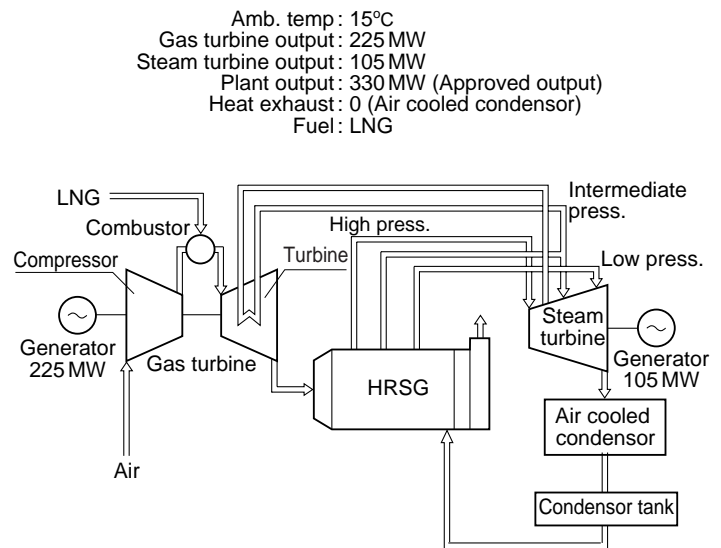


Fig. 1 Flow chart of "H" series trial operation

prevent shaft vibration due to its asymmetrical thermal deformation, the steam passages are arranged symmetrically inside the shaft and an advanced sealing mechanism is applied so that the asymmetrical thermal deformation due to uneven temperature distribution inside the rotor is reduced as much as possible.

- (2) There was concern that the metal temperature would rise due to high temperature steam flowing through the interior of the hollowed shaft in the turbine side. In the disassembling inspection after the second trial operation, however, it was confirmed that there was no irregularity in the white metal of the journal bearings.
- (3) Because the amount of cooling air for the turbine vane/blade is remarkably reduced compared with that in conventional air-cooled gas turbines, the turbine outlet gas temperature is higher at the same pressure ratio. Accordingly, the pressure ratio in the "H" series gas turbine is increased from 20 in the "G" series gas turbines up to 25 in the "H" series in order to keep the turbine outlet gas temperature at the same level as in conventional turbines. A new high efficiency compressor has been developed for the compression system. The compressor utilizes three-dimensional skewed vanes, which are designed using the three-dimensional Navier-Stokes flow analysis code. The compressor is a newly developed higher efficiency compressor with the stages reduced by making the chord wider and the aspect ratio lower than those in conventional compressors. In the front stage, MCA (Multiple Circular Arc) blades are adopted in order to restrict the generation of shock waves at the transonic range. CDA (Controlled Diffusion Airfoil) blades are adopted in the middle and rear stages so as to control the boundary layer flow. A



**Fig. 2 Gas turbine combined cycle verification plant ("T" point) at Takasago Machinery Works**

The trial operation of the "H" series gas turbine was conducted at this plant.

prior thorough performance verification has been carried out in order to adopt the new type compressor, with a 0.29 size prototype compressor used.

- (4) A steam-cooled low NO<sub>x</sub> combustor, which has already been used for the 1 500°C class "G" series gas turbine, is adopted as well for the "H" series. This type of combustor has been in commercial operation at the "T" point since 1997.
- (5) A four-stage axial flow type has been developed for the "H" series gas turbine using the latest three-dimensional design system. The first and second stages are steam-cooled, the third stage is air-cooled, and the fourth stage is not cooled. Using the three-dimensional Navier-Stokes flow analysis code, design and analysis have been carried out in order to minimize any profile loss. Furthermore, multi-cascade analysis has been carried out in order to optimize the matching of the velocity triangle at each stage, and unsteady flow analysis has been performed to evaluate the excitation force acting on the blades.
- (6) The turbine airfoils are made of materials (MGA2400 for the vanes and MGA1400 for the blades) developed by MHI. The first stage blades and vanes are directly solidified airfoils.
- (7) The turbine disk is made of 10% Cr steel (MGA10) developed by MHI. This material is superior in high temperature strength compared with conventional materials and permits the temperature of steam recovered from the blades to be set at a higher level.
- (8) The technology for sealing high-temperature and high-pressure steam is one of the important technologies for steam cooling. As a result, many component tests and verification tests have been intensively repeated from the initial stages of de-

velopment. In the high-temperature high-pressure zones, the sealing parts deteriorate in their level of performance due to thermal deformation and wear. Therefore, an optimum sealing design aimed at addressing this problem has been newly developed for the "H" series. Steam leakage affects the plant total thermal efficiency and operational capability of the plant, so that minimizing such leakage is very important.

- (9) Vane-cooling steam is distributed evenly to each vane through a manifold (passage) provided inside the turbine blade ring supporting the vanes. Providing the steam passage inside the blade ring enables the steam temperature to control the tip clearance of the turbine blade, because the steam temperature influences the metal temperature of the blade ring.

### 3. Second trial operation of "H" series gas turbine

#### 3.1 Outline of trial operation

The second trial operation of the M501H gas turbine was conducted at the gas turbine combined cycle verification plant ("T" point) installed at the Takasago Machinery Works, MHI (**Fig. 2**).

This plant, which had usually been operated for verifying the long-term reliability of the M501G gas turbine, was modified temporarily for the trial operation of the M501H gas turbine.

#### 3.2 Results of trial operation

In the second trial operation, special measurements of more than 2 000 points were made in order to verify the performance, combustion, mechanical properties, and reliability of the gas turbine. Thermodynamic functions were included in these measurements. For instance, the steam temperature, pressure, and flow rate at the turbine outlet are important parameters for the cooling system of the gas turbine because they influence the condition of the gas turbine-cooling steam. The steam-cooled combustor and the turbine vane/blade play the same role as the reheater of the HRSG in the plant system. Accordingly, the steam temperature and pressure after cooling are inlet steam conditions of the intermediate-pressure steam turbine. Hence, they are used as parameters for deciding the operation condition and reliability of the steam turbine. As described above, for a combined cycle power generation plant using a steam-cooled gas turbine, it is very important to monitor and control the thermodynamic functions of the plant system.

The second trial operation was conducted from December 2000 through March 2001. During this trial operation, the warming test, start-up test, no-load rated speed operation, cooling steam-switching test, and parallel load change test for the steam-cooled

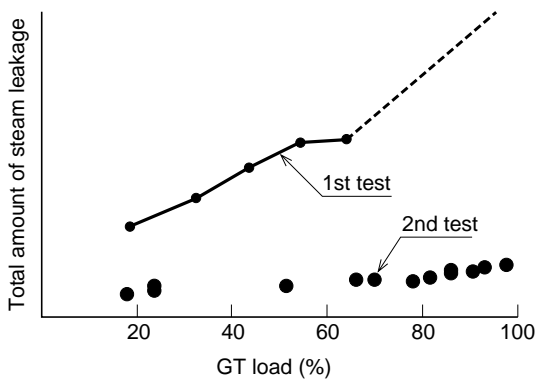


Fig. 3 Relation between load and steam leakage in the second trial operation

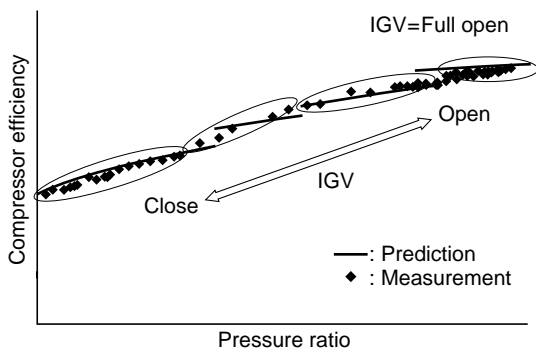


Fig. 4 Relation between compression ratio and compressor efficiency in the second trial operation

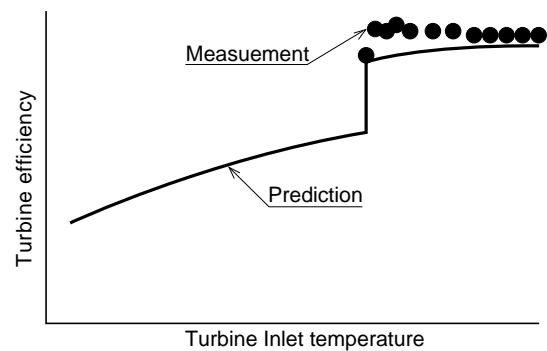


Fig. 5 Relation between turbine inlet temperature and turbine efficiency in the second trial operation

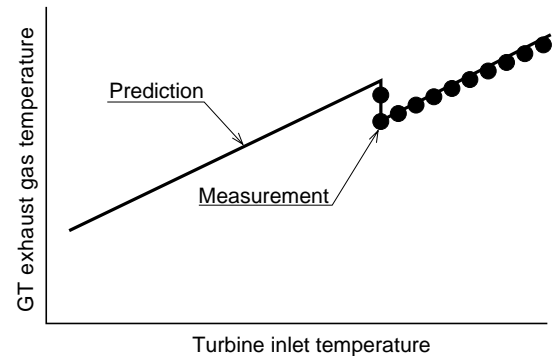


Fig. 6 Relation between gas turbine inlet temperature and outlet temperature in the second trial operation

parts were conducted. A long-term heat run was then successfully conducted at an operation of 225 MW in the gas turbine and 105 MW in the steam turbine, or 330 MW in total, which is the approved output of the “T” point. After the heat run, load rejection tests were successfully carried out, so that the dynamic characteristic data of the plant were obtained. No irregularities were observed in the transient characteristics. The following are the principal results obtained from the second trial operation.

(1) Steam leakage

The amount of steam leakage was significantly reduced, compared with that in the first trial operation, by improving the steam sealing design of each part. The amount of reduced leakage was confirmed to be at a level capable of being commercialized safely (Fig. 3).

(2) Component efficiencies of compressor and turbines

In order that the M501H gas turbine can achieve the total thermal efficiency, the individual element efficiencies of the compressor and the turbines must achieve their targets, respectively. According to the measurements in each IGV opening angle, the efficiency of the compressor was confirmed to achieve the predicted performance in any opening angle. The reliability was verified by measuring the surge margin, suction flow rate, stage load, total pressure and total temperature distributions in the radial and circumferential directions of the

representative stage, as well as vibration and pressure fluctuations in the front stage at a rotating stall (Figs. 4 and 5).

The point where the turbine efficiency rises suddenly at a constant turbine inlet temperature shows a change caused by operating the Inlet guide vanes (IGV) at the compressor inlet. Results of measurements of the pressure and temperature for each stage also verified that the turbine performance as well as the gas turbine outlet gas temperature was as estimated (Fig. 6).

(3) Metal temperature of steam-cooled turbine vane/blade

Special measurements were made of over 400 points for the steam-cooled turbine vane/blade. The measurements were found to conform with the estimated values; therefore, high vane/blade reliability as well as high estimating accuracy was verified. In addition, the thermal stress distribution calculated from the metal temperatures of the cooled airfoils showed the cooled airfoils to have the fatigue lives planned (Figs. 7 and 8).

(4) Other items

According to the measured metal temperature of the turbine side journal bearing, the bearing metal was sufficiently cooled during the long-term heat run, that is, no problem was observed.

A detailed analysis of the shaft vibration data showed the second trial operation to be just as

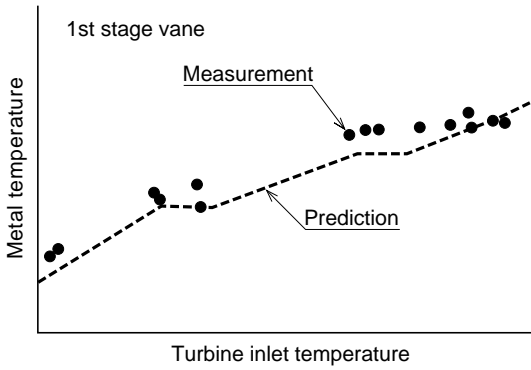


Fig. 7 Relation between turbine inlet temperature and turbine first stage vane metal temperature in the second trial operation

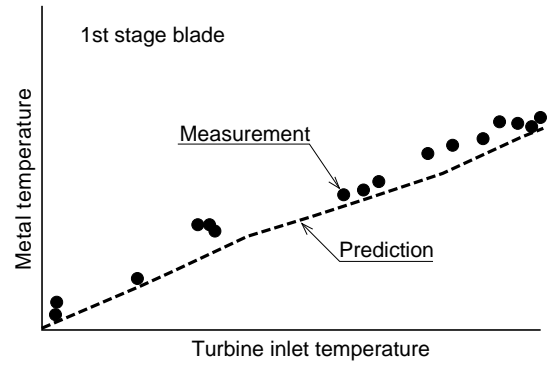


Fig. 8 Relation between turbine inlet temperature and turbine first stage blade metal temperature in the second trial operation

sufficiently stable as the first trial operation.

**4. Conclusion**

The “H” series gas turbines are characterized by turbine vane/blade cooled by steam supplied from the bottoming cycle, an approach that differs from conventional gas turbines. As a result, both the plant total thermal efficiency and the output are remarkably improved compared with the “G” series. The construction of the newly developed gas turbine follows a reliable construction proven by conventional gas turbines. However, the performance of new component technologies were verified through many component tests conducted prior to application. As a result, the gas turbine was designed and manufactured in a period as short as thirty months from the start of development. Further, the first trial operation could achieve a plant output of 220 MW, that is, the first step verification was successfully completed. On the basis of the results of the first trial operation, the steam sealing system and other aspects of the gas turbine were improved. Component tests and prior verification tests were carried out for six months after the first trial operation. A heat run was finally conducted during the second trial operation at a total output of 330 MW, the approved output for the “T” point.

Through these two trial operations, the stable operation of the steam-cooled rotor and the cooling characteristics of the steam-cooled vanes and blades were verified. Also, the amount of leakage of cooling steam and the elemental efficiencies of the compressor and turbines achieved their respective target values. Thus, the “H” series gas turbines were verified to achieve the plant total thermal efficiency

exceeding that of conventional gas turbines.

Since LNG-fired combined cycle power generation plants have low emissions, world attention has focused on these systems as a key for helping to protect against global warming, with the result that they are rapidly spreading in America and Europe. Under such conditions, “H” series gas turbines that can achieve even greater efficiencies can be expected to spread as a leading machine for helping to prevent global warming, and MHI expects them to be able to contribute to solving global environmental problems more in the future.

**References**

- (1) Umemura et al., Development and Operating Status of “1500°C Class” Gas Turbine
- (2) Maekawa et al., Development of H Series Gas Turbine & Aero-engine Congress & Exhibition (2001) New Orleans, USA
- (3) Tsukagashi et al., The Latest Large-Capacity High-Efficiency Gas Turbine, GTSJ,2002-1



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