Design of 600°C Class 1 000 MW Steam Turbine

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In Japan, all large capacity fossil-fuel power plants are supercritical units and a steam condition of 246 kgf/cm²G, 538/566°C has been adopted. Through extensive development work, the design and material technologies for steam turbines with a 593°C steam temperature have been established, and the steam condition of 246 kgf/cm²G, 538/593°C was applied to the 700 MW steam turbine of Hekinan No.3 Unit, Chubu Electric Power Co., Inc. for the first time in Japan. This unit has been operating successfully since it started commercial operation in April, 1993. Mitsubishi Heavy Industries, Ltd. (MHI) designed 1 000 MW turbines with a steam condition of 600°C class main and reheat steam temperature for the first time in Japan, even though in the world, applying the latest technologies developed for 600°C class application.

1. Introduction

Problems related to the greenhouse effect from carbon dioxide and to saving of resources have been discussed recently, and attempts have been made to enhance efficiency by high-temperature and high-pressure steam conditions, as well as to improve the internal efficiency of turbines.

With the object of realizing steam temperatures in the 600°C class, a wide ranges of development activity has been carried out including a feasibility study of a ultrahigh-temperature turbine at Wakamatsu High-Temperature Project, Electric Power Development Co., Ltd., and design and material technologies for high-temperature use of steam turbines have been verified[(1)].

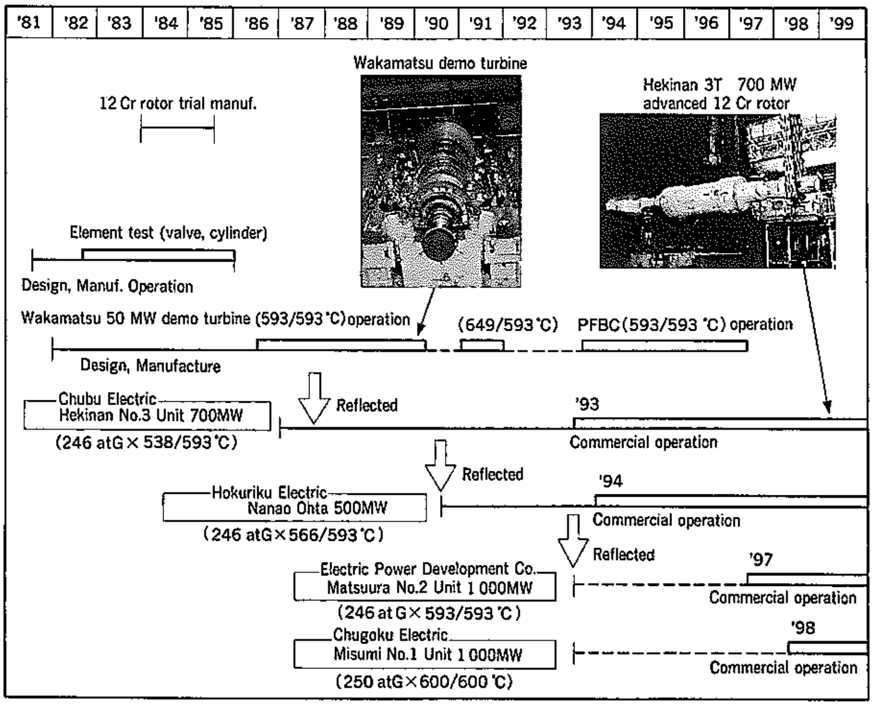
The technology of a large-capacity and high-temperature turbine has been established in the 700 MW unit (reheat steam temperature 593°C) at Hekinan No. 3 Unit, Chubu Electric Power Co., Inc. by applying the high-temperature element technology verified at high-temperature. This unit has been running steadily since the operation was started in April, 1993[(2)]. Furthermore, in 1 000 MW units at Matsuura No. 2 Unit, Electric Power Development Co., Ltd., and Misumi No. 1 Unit, Chugoku Electric Power Co., Inc., the 600°C class is applied to both main steam and reheat steam temperature, and both are now in the process of manufacture. Besides, in these 1 000 MW units, cycle efficiency has been enhanced by heightening the main and reheat steam temperature and, in addition, the latest flow dynamic analysis method for enhancing internal efficiency has been applied to reaction blades and the 46-inch ISB (Integral Shroud Blade) in the low-pressure end blade.

2. Outline of units

The history of development for high-temperature applications and operation results are shown in **Table 1**. A sectional view of assembly of a 600°C class 1 000 MW steam turbine is shown in **Fig. 1**, and the major specifications in **Table 2**.

The turbine is a cross compound type using both a high-

Table 1 Development and experience for increase in inlet steam temperature



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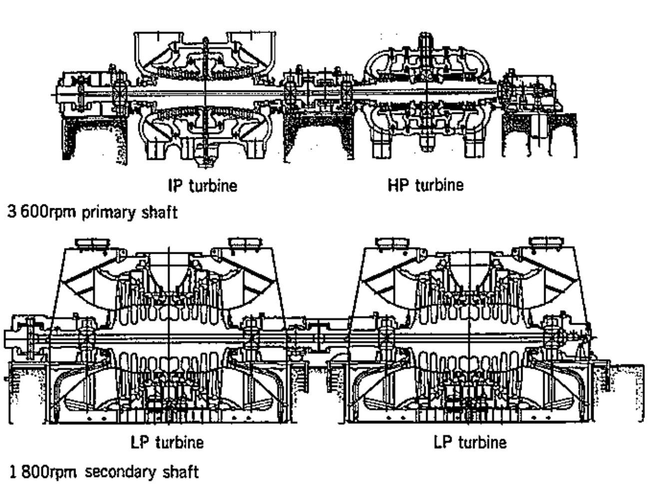
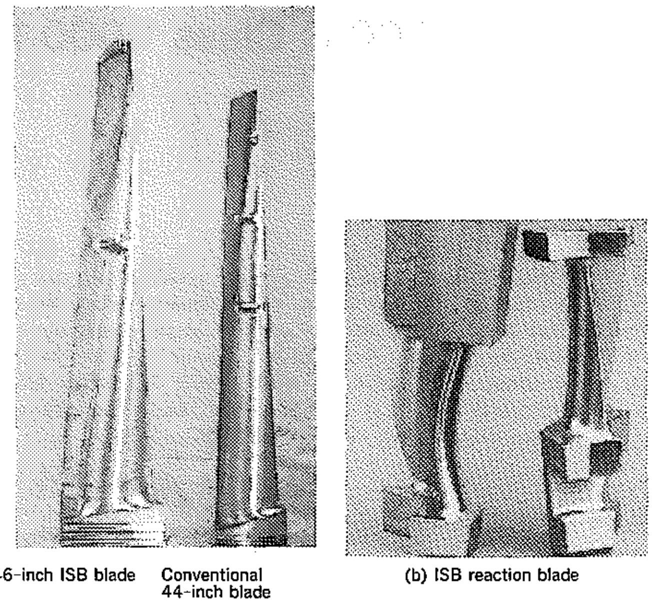


Fig. 1 600℃ class 1000 MW steam turbine longitudinal section

Table 2 Major specifications of steam turbine

Item	Specifications	
Unit name	Matsuura No.2 Unit, Electric Power Development Co.	Misumi No.1 Unit, Chugoku Electric Power Co.,Inc.
Type	Cross compound, 4 exhaust flows, reheat, regenerative condensing type	
Output (rated)	1 000 000 kW	
Steam condition		
(Main steam press.)	24.1 Mpa (246 kgf/cm²)	24.5 Mpa (250 kgf/cm²)
(Main steam temp.)	593°C	600°C
(Reheat steam temp.)	593°C	600°C
Rotating speed	Primary shaft 3 600 rpm Secondary shaft 1 800 rpm	
Vacuum	722 mmHg	
End blade length	1 170 mm (46 inches)	
Feed water heater	8 stages	



(a) 46-inch ISB low-press. end blade (b) ISB reaction blade

Fig. 2 46-inch ISB LP end blade and ISB reaction blade
As compared with conventional 44-inch blades, the 46-inch ISB has been further enhanced in its performance and reliability. The ISB reaction blade is a high-efficiency blade whose secondary flow loss has been decreased.

Table 3 Materials of HP turbine

	Main steam temp. 600°C class	Main steam temp. 538°C (conventional)
Rotor	Advanced 12 Cr forging (TMK-1, TMK-2)	Cr-Mo-V forging
Nozzle chamber	12 Cr cast steel	2 ¼ Cr-1 Mo cast steel
Inner casing	12 Cr cast steel	1 ¼ Cr-1/2 Mo cast steel
No.1 blade ring	12 Cr cast steel	1 ¼ Cr-1/2 Mo cast steel
No.2 blade ring	2 ¼ Cr-1 Mo cast steel	1/2 Cr-1/2 Mo cast steel
Outer casing	2 ¼ Cr-1 Mo cast steel	1 ¼ Cr-1/2 Mo cast steel
Rotating blade	Refractory alloy (R-26)	12 Cr forging
Main steam stop valve	9 Cr forging	2 ¼ Cr-1 Mo forging
Main steam governing valve	9 Cr forging	2 ¼ Cr-1 Mo forging

pressure and medium-pressure turbine as primary shafts and two low-pressure turbines as secondary shafts. The design and material technology of 600°C class steam turbines of medium-pressure turbines has been established in Hekinan No. 3 Unit, Chubu Electric Power Co., Inc. To be applicable to 600°C class high-temperature main steam, the design features are high-temperature techniques in high-pressure turbines including high-temperature materials such as advanced 12 Cr steel rotors (TMK-1, TMK-2).

Furthermore, to enhance steam turbine internal efficiency, in addition to improvement of cycle efficiency by increasing the temperature of main steam and reheat steam, the rotating parts comprise the 46-inch ISB [**Fig. 2** (a)], the largest one in use as the low-pressure end blade for a 1 000 MW thermal power turbine in Japan, and the ISB reaction blade [Fig. 2 (b)] designed by the latest three-dimensional flow analysis, including the low-pressure end blades groups.

3. Design features of 600°C class high-pressure turbine

In high-temperature turbines at Matsuura No. 2 Unit and Misumi No. 1 Unit, the following design points are taken into consideration for application to high-temperature of main steam.

3.1 Material for high-temperature

The materials used in high-pressure turbines of 600°C class main steam temperature are shown in **Table 3** in comparison with conventional high-pressure turbines at main steam temperature of 538°C. In high-pressure turbines, ferritic heat-resisting steel materials are widely used, such as advanced 12 Cr forging, 12 Cr cast steel, and 9 Cr forging. In high-temperature rotating blades, austenitic refractory alloys are used, while advanced 12 Cr forging (TMK-1, TMK-2) having sufficient creep rupture strength for operation at 600°C class high-temperature is used as the rotor material. In the journal and thrust collar section of 12 Cr rotor, overlay-welds are built up by low Cr welding material in order to avoid machining wear of the bearing white metal.

As materials for stationary parts, 12 Cr cast steel (MJC-12) having excellent creep rupture strength is used in the nozzle chamber, inner casing, and No. 1 blade ring.

9 Cr forging is used in the main stop valve at the high-pressure turbines inlet, governing valve, and connection piping between valve and casing.

3.2 Construction of high-pressure turbine

In the design of high-pressure turbine for high-temperature, construction parts exposed to high-temperature are of compact design. A cooling structure is also employed to ensure sufficient reliability against creep and thermal fatigue.

The features of the high-pressure turbine are shown in **Fig. 3**. A double flow type welded nozzle chamber is used, which has made possible compact design of the inner casing. In the rotor axial center, a cooling hole is provided in the control

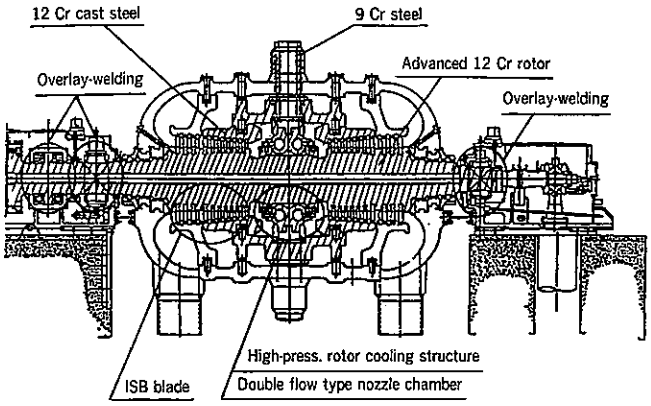


Fig. 3 Features of HP turbine design
Shaded area denotes the application of high-temperature material in comparison to conventional 538°C design.

stage disc, and the rotor is effectively cooled by supplying control stage outlet steam to the space between the nozzle chamber and the rotor as shown in **Fig.** 4(b).

In the rotating blades, reliability at high-temperature is enhanced by employing the ISB blade manufactured by one-piece machining of shroud and blade without tenon.

4. Development and verification of 600°C class high-pressure turbine

4.1 Cooling structure of high-pressure rotor

A cooling hole flow characteristics test was conducted by using a rotation test model simulating the control stage rotor with cooling hole, nozzle chamber as shown in Fig.4 (a), and the relation between flow rate and pressure difference was investigated. The test was carried out in the flow rate range to induce turbulent flow in the cooling hole, and by varying the rotating speed, it was confirmed that there is no change in the flow characteristics of the cooling hole.

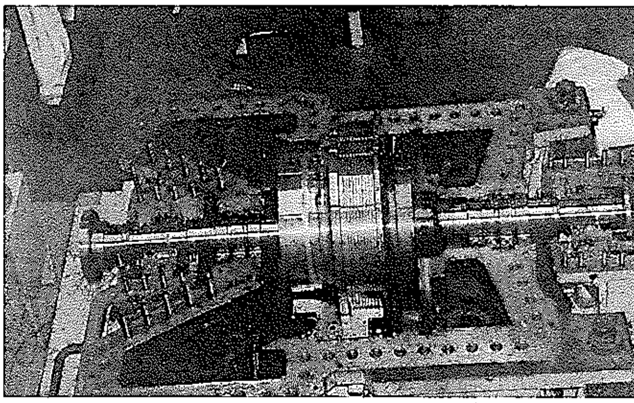
Using the obtained results, both the flow and heat balance were calculated in consideration of high-temperature leakage steam at the control stage nozzle outlet, low-temperature steam at the control stage rotating blade outlet, and mixed steam of the two. The mixed steam temperature in the space between the nozzle chamber and the rotor was then evaluated, and it was confirmed to be sufficiently cooled to target temperature. As shown in Fig. 4 (b), it is important in the design to take into consideration both rotor cooling performance and control stage internal efficiency by evaluating the required low-temperature steam quantity with high precision.

4.2 Advanced 12 Cr (TMK-1, TMK-2)

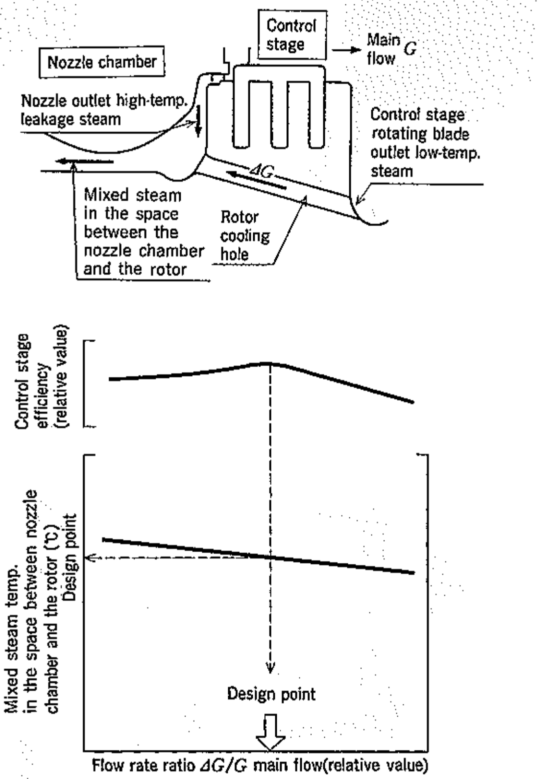
Advanced 12 Cr rotor material (TMK-1) has the feature that its Mo equivalent content is 1.5, and this material is superior in high-temperature strength to conventional rotor materials. TMK-2 is also further enhanced in high-temperature strength by addition of W to nearly 2%. This rotor material has already been treated by refining, and favorable results are obtained in ultrasonic examination of the center bore and material tests.

4.3 Nozzle chamber of double flow type

The nozzle chamber is exposed to the most severe steam conditions among stationary parts. At superhigh-temperature, therefore, it is important to guarantee its reliability. To obtain



(a) Testing apparatus for flow characteristics of cooling hole



(b)Flow balance characteristics of control stage

Fig. 4 Cooling characteristics for HP rotor and control stage efficiency
By verifying the flow characteristics of the cooling hole in the control stage, the rotor cooling and control stage efficiency can be optimized.

sufficient high-temperature strength, the nozzle chamber main body is made of 12 Cr cast steel and the nozzle ring of super 9 Cr steel.

In the nozzle chamber of the complicated shape, the local stress elevation due to the stress concentration is observed, but this can be kept down to an allowable stress level by optimizing the internal shape and reinforced structure. **Fig. 5** shows calculation models and temperature distribution. Moreover, through the evaluation of the life by creep analysis, the sufficient structural reliability has been confirmed.

4.4 Overlay-welding on rotor bearing section

As measures against machining wear of 12% Cr rotor bearings, model test pieces simulating the journal and thrust were overlaid with low Cr welding material, and a manufacturing method was established. A verification test was also

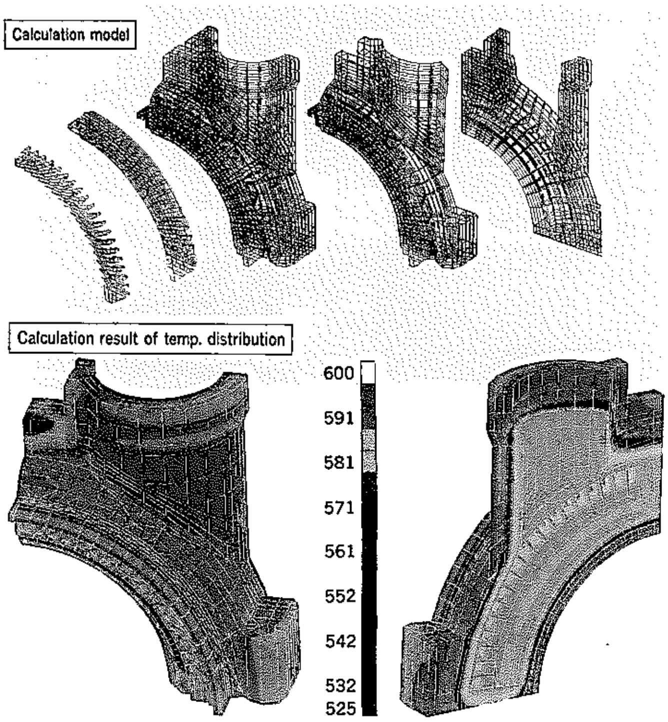
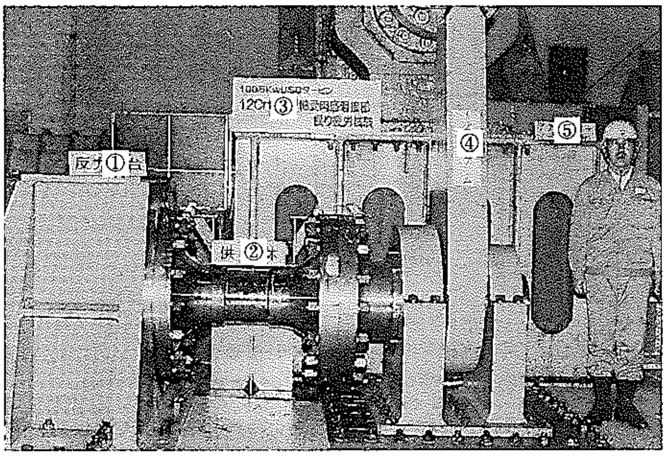


Fig. 5 Calculation model and temperature distribution of double flow nozzle chamber

Analyzed by using a model including nozzle vane. A highly reliable design is realized by optimizing the internal shape and reinforcing structure to cope with local stress elevation.



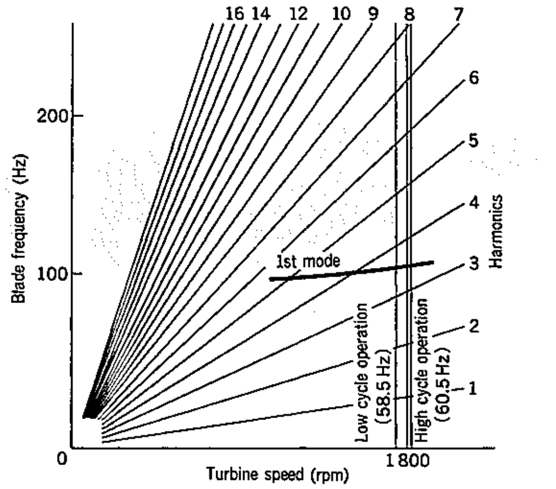
① Reaction platform ② Test model
③ 1 000 MW USC turbine 12 Cr rotor bearing overlay-welding torsional fatigue test
④ Torque propagation arm ⑤ Actuator

Fig. 6 Rotor torsional fatigue test instrument

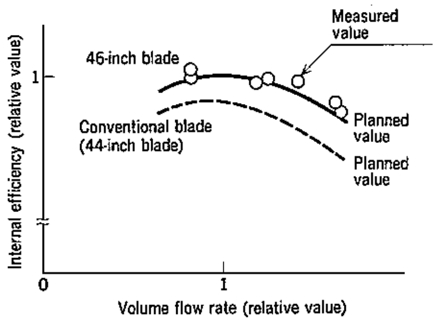
By overlay-welding model of full scale shaft and actual shape, rotor torsional fatigue is tested, and reliability is confirmed.

conducted to investigate the material characteristics and confirm the reliability by torsional fatigue test of the full scale model shaft.

In the investigation of the material characteristics, a homogeneous overlay-welding with Cr concentration of 2% or less was obtained. Regarding the mechanical properties such as 0.2% yield stress and absorption energy, the required specifications were satisfied. To evaluate the fatigue strength against rotor torsional torque, a rotor torsional fatigue test was conducted by using an overlay-welding model of a full scale shaft and actual shape as shown in **Fig. 6**.



(a) 46-inch ISB vibration characteristics



(b) Turbine internal efficiency

Fig. 7 Characteristics of vibration and turbine internal efficiency for 46-inch ISB

In vibration frequency characteristics, resonance is completely avoided in modes of 7 harmonics or less, and the turbine performance is obtaind high efficiency as initially planned.

The result of the test showed it to be completely reliable in the load condition of stress and cycle during the entire life of the actual machine. Moreover, by loading a stress until fatigue crack was formed, the design S-N curve was found to be adequate, and it was confirmed that the low cycle fatigue strength is not reduced with the effect of residual stress.

An overlay-welding technology of highly reliable bearings has thus been established.

4.5 Low-pressure end blades of 46-inch integral shroud blade

The 46-inch ISB low-pressure end blades are highly reliable blades designed on the basis of good results of the 25-, 29.5-, 33-, and 41-inch ISB low-pressure end blades already developed and employed in plants. In the final stage of development, a rotating vibratory test using full 46-inch blades was conducted, and vibratory characteristics were verified to conform to the prediction. Furthermore, a steam load test was conducted on a 1/2 scale model turbine, and performance and reliability were comprehensively evaluated in the actual steam conditions.

This 1/2 scale model turbine comprises multiple stages and is thus able to test not only the end stages but also the upstream stages. The turbine performance and blade vibration were confirmed in the test by varying the steam flow rate and condenser vacuum over a wide range that sufficiently covered the actual operating range.

In the vibration frequency characteristic, as shown in **Fig.** 7 (a), it was confirmed that resonance was completely avoided in the vibration modes of 7 harmonics and less. The results of performance measurements are given in Fig. 7 (b), and the performance was obtained high efficiency as initially planned. From these results, the validity of the fluid dynamic design philosophy[4] applied to fully three-dimensional design blades has been verified.

5. Conclusions

On the basis of wide-ranging development for high temperature and high-pressure and results derived from existing units, steam turbines of 600°C class of main steam and reheat steam temperature were planned in 1 000 MW supercritical units. In such steam conditions, commercial operation is scheduled to start in 1997 for the Matsuura No.2 Unit and in 1998 for the Misumi No.1 Unit. Mitsubishi Heavy Industries, Ltd. is continuing to make efforts aimed at development of highly reliable high-performance steam turbines.

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