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 24.1 MPag, 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 24.1 MPag, 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 class turbines with more advanced steam conditions of 600°C class main steam and reheat steam temperatures for the first time in Japan, applying the latest technologies developed for 600°C class application.

Key Words: Steam Turbine, Fossil Fuel Fired Power Generation, Energy Saving, Blade, Optimum Design, Structural Analysis, Material Testing

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 improve the efficiency of the steam turbine plant by high-temperature and high-pressure steam conditions, as well as to enhance the internal efficiency of

turbines.

With the object of realizing steam temperatures in the 600°C class, a wide range of development activity has been carried out including verification test of a ultrahigh-temperature turbine at Wakamatsu High-Temperature Project, Electric Power Development Co., Ltd., whereby design and material technologies for high-temperature use of steam turbines have been verified.

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 technologies verified at Wakamatsu High-Temperature Project. This unit has been running steadily since the operation was started in April, 1993⁽²⁾. Furthermore, in 1 000 MW class units at Matsuura No. 2 Unit, Electric Power Development Co., Ltd., Misumi No. 1 Unit, Chugoku Electric Power Co., Inc. and Tachibanawan No. 2 Unit, Electric Power Development Co., Ltd., the main steam and reheat steam temperatures of 600°C class are applied, and they are now under construction, exclusive of Matsuura No. 2 Unit which will start

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Table 1 Development and experience for increase in inlet steam temperature

Fig. 1 600°C class 1 000 MW steam turbine longitudinal section

commercial operation in July, 1997. In these 1 000 MW class units, cycle efficiency has been improved by elevating the main and reheat steam temperatures and, in addition, the latest flow dynamic analysis method for enhancing the internal efficiency has been applied to reaction blades and the 46-inch ISB (Integral Shroud Blade) low-pressure end blades.

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.

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.	Tachibanawan No.2 Unit Electric Power Development Co.
Type	Cross compound, 4 exhaust flows, reheat, regenerative condensing type		
Output (rated)	1,000,000 kW		1,050,000 kW
Steam condition			
(Main steam press.)	24.1 MPag	24.5 MPag	25 MPag
(Main steam temp.)	593°C	600°C	600°C
(Reheat steam temp.)	593°C	600°C	610°C
Rotating speed	Primary shaft 3,600 rpm Secondary shaft 1,800 rpm		
Vacuum	5.06 kPa		
End blade length	1,170 mm (46 inches)		
Feed water heater	8 stages		

The turbine is a cross compound type using both a high-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 of main steam, high-temperature techniques are applied in high-pressure turbines including high-temperature materials such as advanced 12Cr steel rotors (TMK-1, TMK-2)^{(3),(4)}.

Furthermore, to enhance the steam turbine

46-inch ISB blade Conventional
44-inch blade

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

(b) ISB reaction blade

Fig. 2 46-inch ISB LP end blade and ISB reaction blade

internal efficiency, in addition to improvement of cycle efficiency by increasing main steam and reheat steam temperatures, the 46-inch ISB low-pressure end blades [Fig. 2(a)] and ISB reaction blades [Fig. 2(b)] are used for the advanced technology. The 46-inch ISB is the largest one in use as the low-pressure end blade for 1,000 MW class thermal power plants in Japan. ISB reaction blades are adopted for higher reliability under high temperature compared with conventional shroud and tenon riveting type blade. Besides, ISB blades are designed through the latest 3-D flow analysis.

3. Design Features of 600°C Class High-Pressure Turbine

In high-temperature turbines at Matsuura No. 2 Unit, Misumi No. 1 Unit and Tachibanawan No. 2 Unit, the following advanced design concepts and special features are applied for operation under 600°C class high-temperatures of main steam.

3.1 Materials for 600°C class main steam temperatures

The materials used in high-pressure turbines of 600°C class main steam temperatures 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 12Cr forging, 12Cr cast steel, and 9Cr forging. In high-temperature rotating blades, austenitic refractory alloys are used, while advanced 12Cr forging (TMK-1, TMK-2) having sufficient creep rupture strength for operation at 600 class high-temperatures is used as

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-½ Mo cast steel
No.1 blade ring	12 Cr cast steel	1 ¼ Cr-½ Mo cast steel
No.2 blade ring	2 ¼ Cr-1 Mo cast steel	½ Cr-½ Mo cast steel
Outer casing	2 ¼ Cr-1 Mo cast steel	1 ¼ Cr-½ 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

Fig. 3 Features of HP turbine design

the rotor material. In the journal and thrust collar section of 12Cr 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, 12Cr cast steel (MJC-12) having excellent creep rupture strength is used in the nozzle chamber, inner casing, and No. 1 blade ring. 9Cr 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 the high-pressure turbine, component parts exposed to high-temperature designed compactly. 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. The materials which have been newly developed for high temperature application and used in the high pressure turbine are marked with oblique line. 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 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, the reliability at high-temperature is enhanced by the ISB blade.

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 a rotation test model simulating the control

(a) Test facility of cooling hole flow characteristics

(b) Flow balance characteristics of control stage

Fig. 4 Cooling characteristics for HP rotor and control stage efficiency

stage rotor with cooling hole, nozzle chamber as shown in Fig. 4(a). The test was carried out in the flow rate range of turbulent flow in the cooling hole, and by varying the rotating speed. As a result, it was confirmed that there is no change in the flow characteristics of the cooling hole.

From the results, both the flow and the heat balance were calculated in consideration of high-temperature leakage steam ($\Delta GN(\oplus)$) at the nozzle outlet, low-temperature steam ($\Delta GN(\ominus), \Delta G$) from the control stage outlet, and mixed steam.

where,

$$\Delta GM = \Delta G + \Delta GN(\oplus)$$

(In the case of a plus reaction)

$$\Delta GM = \Delta G - \Delta GN(\ominus)$$

(In the case of a minus reaction)

reaction (R_p) definition:

$$R_p = \frac{P_{s1} - P_{s2}}{P_T - P_{s2}}$$

ΔGN flow direction depends on a reaction (R_p) at the hub side of the control stage. In the case of a plus reaction ($R_p > 0$), ΔGN flows in the $\oplus$ direction as shown in Fig 4(b).

By contraries, in the case of a minus reaction ($R_p < 0$), ΔGN flows in the $\ominus$ direction as shown in Fig 4(b) and is divided from ΔG . So ΔGN is not high-temp. leakage steam but low-temp. steam supplied from rotor cooling holes.

Therefore when the flow and a heat balance are calculated, both a plus and a minus reaction should be taken into consideration to optimize rotor cooling effect and control stage internal efficiency.

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 a target temperature. As shown in Fig. 4(b), it is important in the design to take into consideration both rotor cooling effect and control stage internal efficiency by evaluating the required cooling steam quantity with high precision.

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

Advanced 12Cr 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%. Full size HP, IP rotors of TMK-1, TMK-2 were produced and then verification research was carried out. The results indicate that the TMK-1, TMK-2 rotors are quite applicable to a 600°C class steam turbines.

4.3 Nozzle chamber of double flow type

The nozzle chamber is exposed to the most severe steam conditions among stationary parts. To obtain

sufficient high-temperature strength, the nozzle chamber main body is made of 12Cr cast steel and the nozzle ring is of super 9Cr steel. The shape of the nozzle chamber is complicated, so the local peak stress increases due to the stress concentration. But then the optimum design of the internal shape and reinforced structure makes it possible to reduce the stress to sufficiently less than an allowable stress. Figure 5 shows calculation models and temperature distribution. From the evaluation of the life by creep analysis, the structural reliability has been confirmed sufficiently.

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 conducted to investigate the material characteristics and verify 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 characteristics 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.

The test result 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 occurred, the design S-N curve was found to be valid and it was confirmed that the low cycle fatigue strength is not reduced by residual stress. The highly reliable technology of the overlay-welding on 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 which have already developed and employed in plants. In the final step of the development, the rotating vibratory test by full scale 46-inch blade was conducted, and it was confirmed that the vibratory characteristics coincided to the expected. Furthermore, the steam load test was conducted on a 1/2 scale model turbine, and performance and reliability were comprehensively evaluated in the actual steam conditions.

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

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

Fig. 6 Rotor torsional fatigue test instrument

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 characteristics were verified 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 the vibration modes of 7 harmonics and less was completely tuned. The performance results are given in Fig. 7(b). The turbine internal efficiency was enhanced as

(a) 46-inch ISB vibration characteristics

(b) Turbine internal efficiency

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

initially expected, and that the validity of the fluid dynamic design philosophy⁽⁶⁾ applied to fully three-dimensional design blades has been verified.

5. Conclusion

On the basis of extensive development works for

high temperatures and pressures and results derived from existing units, steam turbines of 600°C class of main steam and reheat steam temperatures were designed in 1000 MW class ultrasupercritical units. Commercial operation in such steam conditions is scheduled to start in 1997 for the Matsuura No. 2 Unit, in 1998 for the Misumi No. 1 Unit and in 2001 for the Tachibanawan No. 2 Unit. Mitsubishi Heavy Industries, Ltd. is continuing to make efforts to aim at the development of highly reliable and high performance steam turbines.

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