Progress of Geothermal Steam Turbine Technology

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1. Introduction

Including those currently under manufacture, Fuji Electric has supplied a total of 44 sets of geothermal steam turbines whose total capacity amounts to 1,432MW. In 1960, we supplied our first turbine to the Hotel Hakone Kowakuen. It was a 30kW turbine, the first geothermal steam turbine in Japan. The second turbine we supplied was a 40MW for El Salvador in 1980. Since then, Fuji Electric has been actively researching and developing geothermal turbines. Numerous operational records have proven the high reliability and efficiency of Fuji Electric's geothermal steam turbines. Since 1984, Fuji Electric has gained as much as a 40% share in the United States, the largest geothermal power generation country in the world. This figure represents geothermal power capacity and excludes binary-type geothermal power generation.

In the 15 years since delivery of the geothermal steam turbine to El Salvador, Fuji Electric has continuously improved its geothermal steam turbines on the basis of its operational experiences. If the turbine for El Salvador is considered a first-generation turbine, the 77.5 MW turbine manufactured for Malitbog Geothermal Power Plant, currently under construction in the Philippines, becomes the fourth-generation turbine.

This paper outlines the progress of geothermal steam turbines and introduces the latest large-capacity standard turbine, the package type standard turbine, and the features of the geothermal steam turbines.

2. Progress of Fuji Electric's Geothermal Steam Turbine

Figure 1 shows the progress of geothermal steam turbine technology from the first to the latest generation. This chapter describes the features of the geothermal steam turbines from the first through the third generation.

2.1 First-generation geothermal steam turbine

Figure 2 shows a sectional view of the first full-scale geothermal steam turbine for El Salvador.

The special feature of this geothermal steam turbine is its double-shell casing construction, which reduces thermal deformation. Technically, it is the same construction as the conventional low pressure steam turbine. The conventional low pressure steam turbine has, however, a triple casing construction. Even though the pressure is about the same, the temperature of the conventional turbine is higher than the geothermal steam turbine. Excepting the first stage blades, all the stationary blades in the high pressure

Fig.1 Progress of geothermal steam turbine technology

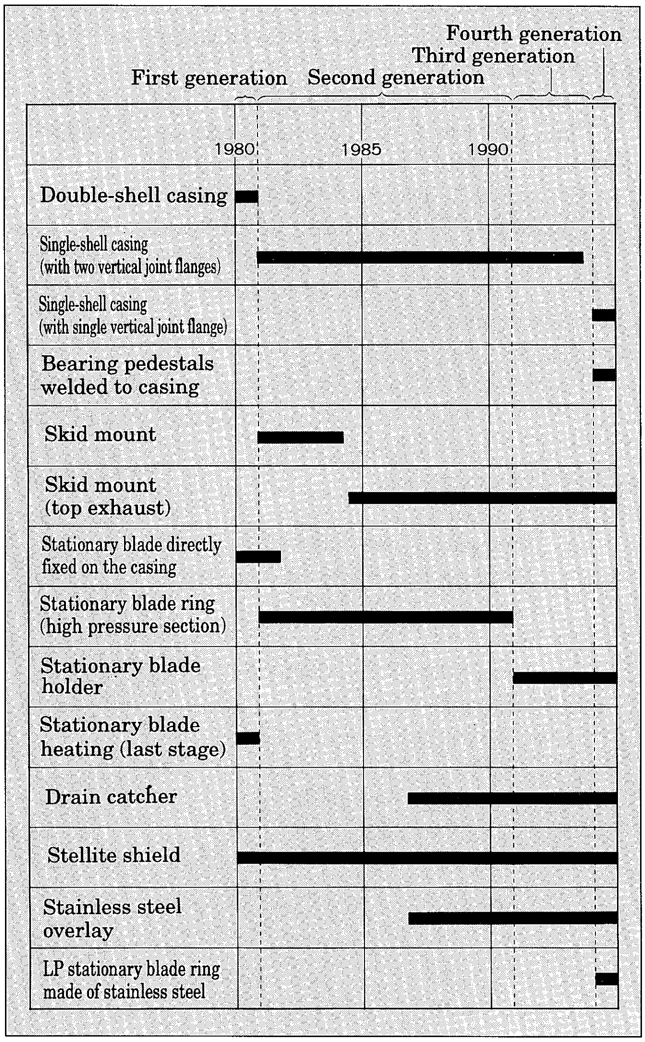


Fig.2 Sectional view of 40MW geothermal steam turbine for El Salvador

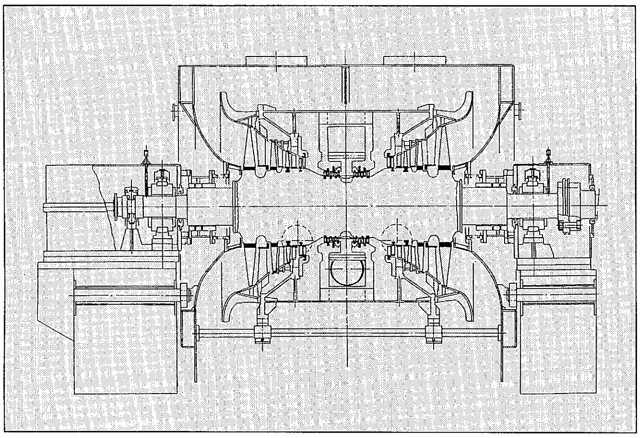
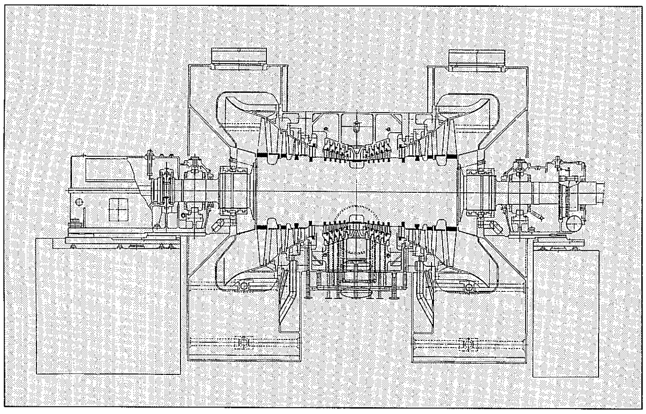


Fig.3 Sectional view of 35MW geothermal steam turbine for Del Ranch



section of the geothermal turbine are directly embedded in the grooves formed by machining the inner wall of the casing. The first stage blades are embedded in the removable stationary blade ring to facilitate maintenance.

As a countermeasure for erosion due to the water droplets, steam is drawn into the hollow parts of the last stage stationary blades. The drain, in the form of a film, is heated and evaporated.

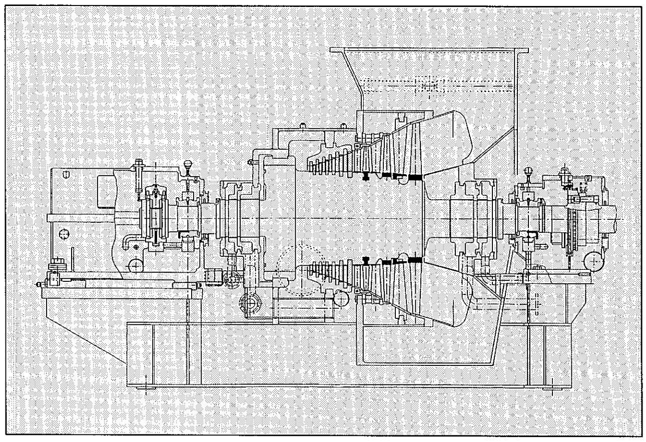
2.2 Second-generation geothermal steam turbine

Figure 3 shows a sectional view of the 35MW geothermal steam turbine for Del Ranch in the United States.

To facilitate assembly and disassembly, a single-shell casing construction is adopted for the second-generation turbine rather than the double shell construction used in the first-generation turbine. The stationary blade ring is adopted for the second-generation for facilitate maintenance instead of stationary blades directly embeded in the casing, which was adopted in the first-generation turbine. Stationary blades are embeded in the stationary blade ring, which can be disassembled independently to the other rings.

As a countermeasure against erosion, drain catchers are provided on the outer rings of the stationary blades (see **5.5**).

Fig.4 Sectional view of 20MW skid-mount type geothermal steam turbine for Okoy



2.3 Third-generation geothermal steam turbine

Figure 4 shows a sectional view of the 20MW geothermal steam turbine for Okoy in Philippines.

This turbine is a single-flow type which utilizes the so-called skid mount system (package type), integrating the turbine and the bed. Downward flowing exhaust (botom exhaust) was adopted in the early stages of the third-generation turbine, but as shown in Fig. 4, upward flowing exhaust (top exhaust) is now primarily used. In the earlier turbines, stationary blades in the high pressure section were embedded in the stationary blade rings stage by stage. But the stationary blades of the third-generation turbines are embedded together in one stationary blade holder. The original purpose of that stationary blade ring construction was to replace only the blades of the stages where scales had accumulated or blades which had been seriously eroded. But in an actual overhaul, it is now the general practice to replace all stages instead of the one or two defective stages. So it takes more time to replace defective stages one by one. Thus, it has become the Fuji Electric standard to embed all stationary blades of the high pressure section into one stationary blade holder, which can be attached to and detached from the casing.

As a countermeasure against corrosion, stainless steel is overlay welded on the inner surface of the stationary blade holder in the high pressure section.

3. Fourth-Generation Large-Capacity Standard Geothermal Turbine

Fuji Electric recently developed a large-capacity geothermal turbine for the Malitbog Geothermal Power Plant. This is the fourth-generation, large-capacity, standard geothermal steam turbine rated at 77.5MW (max. 85.25MW), the largest capacity geothermal turbine Fuji Electric has ever manufactured. It is also the largest single casing geothermal turbine in the world.

Fig.5 Sectional view of 77.5MW geothermal steam turbine for Malitbog Power Plant

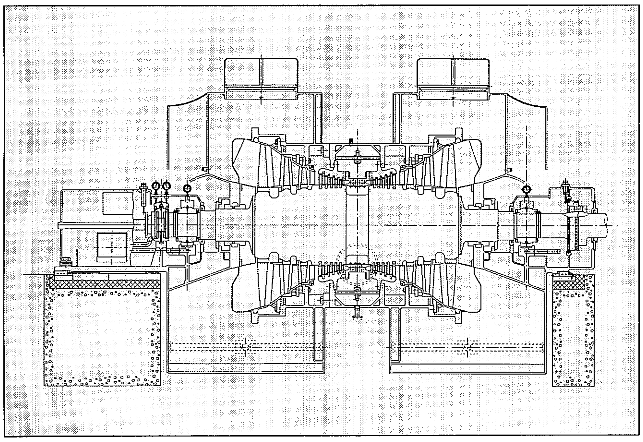
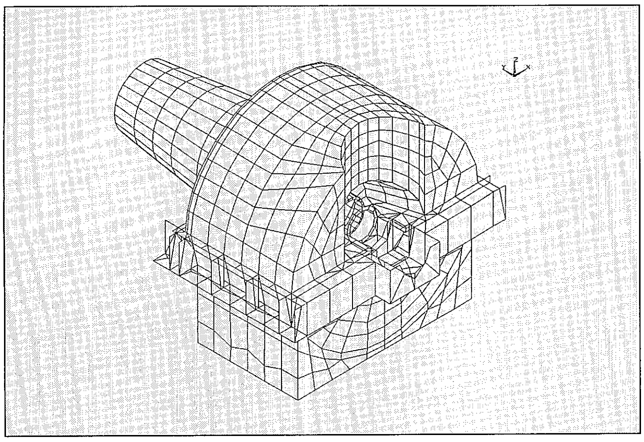


Fig.6 Structural analysis of the casing by FEM



3.1 Optimization of casing construction

Geothermal turbines over 40MW usually adopt a double flow construction. Double flow geothermal turbines up to the third-generation adopt a casing which is composed of three (3) blocks in axial direction. This construction has the two (2) same exhaust casings and a center casing having an inflow part fastened with bolts (see Fig. 3). Bearing pedestals and casings are supported on and connected to the turbine's foundation.

The development of the casing construction was determined on the basis of the concepts below:

(1) reducing the delivery time by adopting a block construction which permits full use of a plano miller

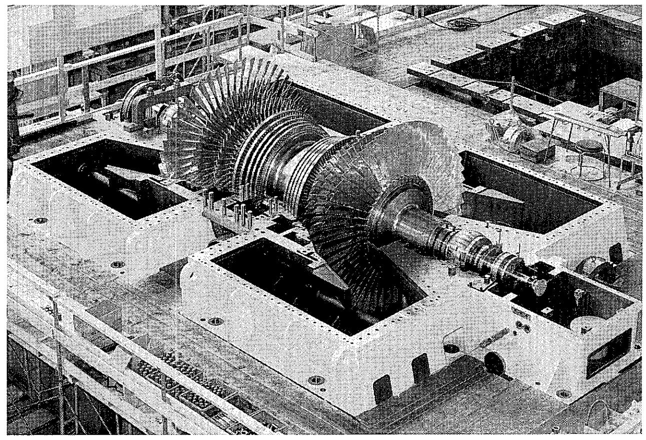
(2) reducing the on-site installation period through completion on of a product in the factory, allowing for transportation restriction

(3) lowering transportation costs by reducing size and weight

(4) ensuring operational reliability through an improvement in the stiffness and vibration characteristics of the casing

Figure 5 shows a sectional view of the fourth-generation geothermal turbine developed based on the above.

Fig.7 77.5MW geothermal turbine under assembly in our factory



The casing has a two-block construction in the axial direction, consisting of the front and rear parts. The casing's dimensions are designed to allow a plano miller to machine in a transverse direction. Furthermore, both the front and rear casings can be set up on the plano miller and continuously machined, one after the other.

The bearing pedestals are welded to the lower half of the casing to reduce the installation period. There are three packages for transportation: one package consists of the front and rear upper casings, and two packages consist of the front and rear lower casings and pedestals. This also aids in reducing the installation period.

As a result, the installation area and weight of the outer casing are reduced by 70% and 65%, respectively.

The bearing pedestals supporting the turbine shaft were welded to the casing as one unit. As a result, it was necessary to verify the effect of the casing deformation on the shaft vibration. For dynamic stiffness analysis in the FEM (Finite Element Method) calculation model, excitation force was given at the bearing-center nodal point where the turbine rotor load was applied. The response displacement at the nodal point was then obtained (see Fig. 6). Figure. 7 shows the assembly conditions, in our factory, of the geothermal turbine for Malitbog.

3.2 Method of fixing the stationary blade holder

In designing internal turbine parts exposed to the flow of geothermal steam, full consideration should be given not only to scaling, erosion, and corrosion during operation but also to facilitated maintenance.

In particular, blade row parts should be designed so that they can be easily maintained during periodic inspection. They should be easily assembled and disassembled to quickly restore normal conditions if any problems should interfere with operation.

In conventional steam turbines, stationary blade holders of upper and lower half are attached by tight-

Fig.8 Structure of stationary blade holder

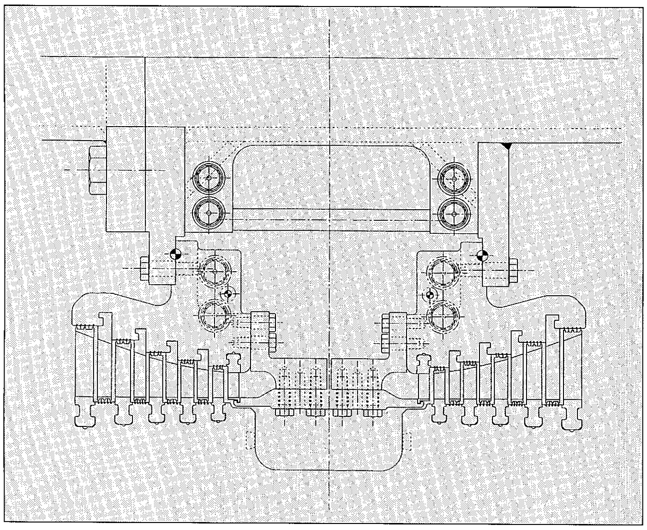
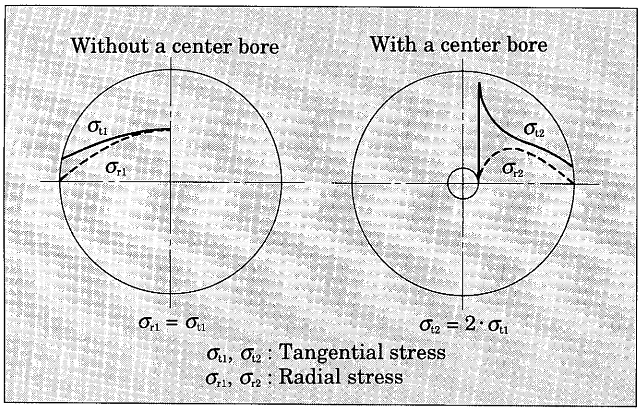


Fig.9 Centrifugal stress of rotating shaft



ening two-split horizontal flanges with bolts to make it airtight preventing leakage of steam at the flanges. They are also fixed to the casing axially by a male-female joint.

If the above method is adopted for geothermal turbines, scales will accumulate on the fitting parts, resulting in sticking the casing and stationary blade holder, making it difficult to disassemble the casing. On the other hand, horizontal flanges must be tightened so that steam does not leak out and cause erosion and corrosion problems.

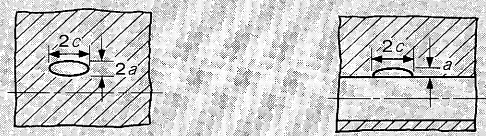
Under these circumstances, the stationary blade holder of the geothermal turbine for the Malitbog Geothermal Power Plant has been developed according to the following concepts:

(1) ensuring the horizontal split flanges (upper and lower flanges) are airtight
(2) ensuring the axial fixing parts are airtight
(3) preventing the casing and the stationary blade holder from sticking
(4) designing the stationary blade holder so that it can be easily assembled, disassembled, and replaced with a spare holder

Figure 8 shows the structure of the stationary blade

Fig.10 Allowable limits of defect dimension in the rotor

Allowable limits of defect dimension in the rotating shaft



Allowable limits of defect dimension (for life of calculation)

$$a_{cr1} = \left(\frac{K_{IC}}{\sigma_{t1}}\right)^2 \cdot \frac{Q}{\pi} \qquad a_{cr2} = \left(\frac{K_{IC}}{\sigma_{t2}}\right)^2 \cdot \frac{Q}{1.21\pi}$$

$$a_{cr1} = 4.84 a_{cr2}$$

Allowable limits of equivalent defect diameter (for ultrasonic inspection)

$$d_{cr1} = \sqrt{10} \cdot a_{cr1} \qquad d_{cr2} = \sqrt{5} \cdot a_{cr2}$$

$$d_{cr1} = 6.84 d_{cr2}$$

K_{IC} : Fracture toughness
Q : Shape parameter of defects
a_{cr1}, a_{cr2} : Allowable limits of defect dimension
d_{cr1}, d_{cr2} : Allowable limits of equivalent defect diameter

Table 1 Delivery history of medium capacity geothermal turbines

Plant name	Operation starting year	Rated output (MW)	Frequency (Hz)
Salton Sea (US)	1981	10	60
Yang Ban Jing (China)	1986	3.18	50
Navy I , Unit 2 (US)	1988	30	60
Navy I , Unit 3 (US)	1988	30	60
Aidlin No.1 (US)	1989	12.5	60
Aidlin No.2 (US)	1989	12.5	60
BLM, Unit 1 (US)	1989	24	60
BLM, Unit 2 (US)	1989	24	60
BLM, Unit 3 (US)	1989	30	60
Navy II, Unit 1 (US)	1989	30	60
Navy II, Unit 2 (US)	1989	30	60
Navy II, Unit 3 (US)	1989	30	60
Palimpinon II, Nasuji (Philippines)	1993	20	60
Palimpinon II, Okoy (Philippines)	1993	20	60
Palimpinon II, Sogongon (Philippines)	1994	20	60
Palimpinon II, Sogongon (Philippines)	1994	20	60

holder designed according to the above concepts. Axial fixing of the stationary blade holder is not done with a conventional male-female joint but by fastening the flanges with bolts.

In order to tight and/or loose bolts for horizontal split flange of stationary blade holder, a handhole is provided with flange on the casing upper half.

This secures the air from escaping at both the axial fixing and horizontal joint flanges. To disassemble the casing, the horizontal joint flange bolts of stationary blade holder are removed, after which the casing upper

Fig.11 Sectional view of skid mount type geothermal turbine for 50Hz use

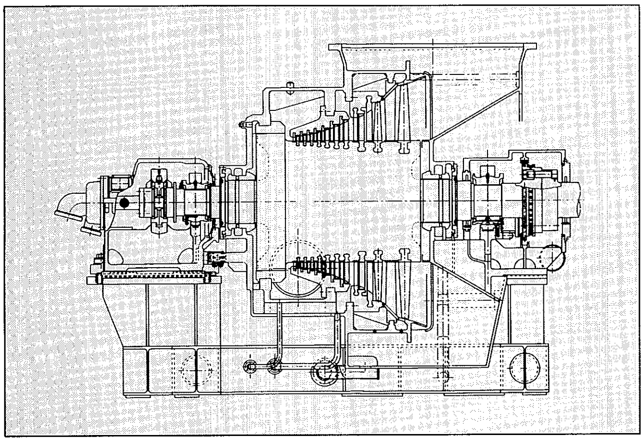
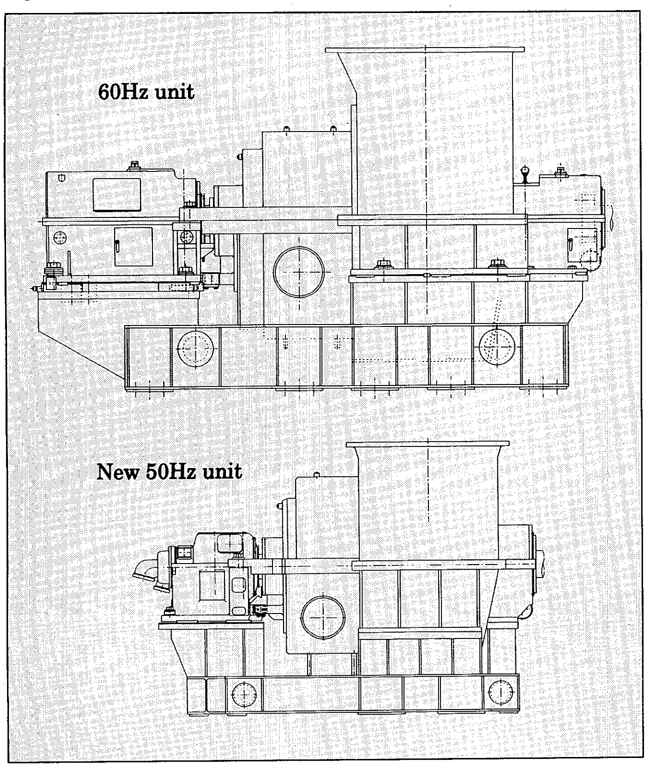


Fig.12 Full views of a 60Hz unit and a new 50Hz unit



half can be lifted together with the upper stationary blade holder.

The stationary blade holder can be disassembled by removing the flange bolts of the axial fixing parts.

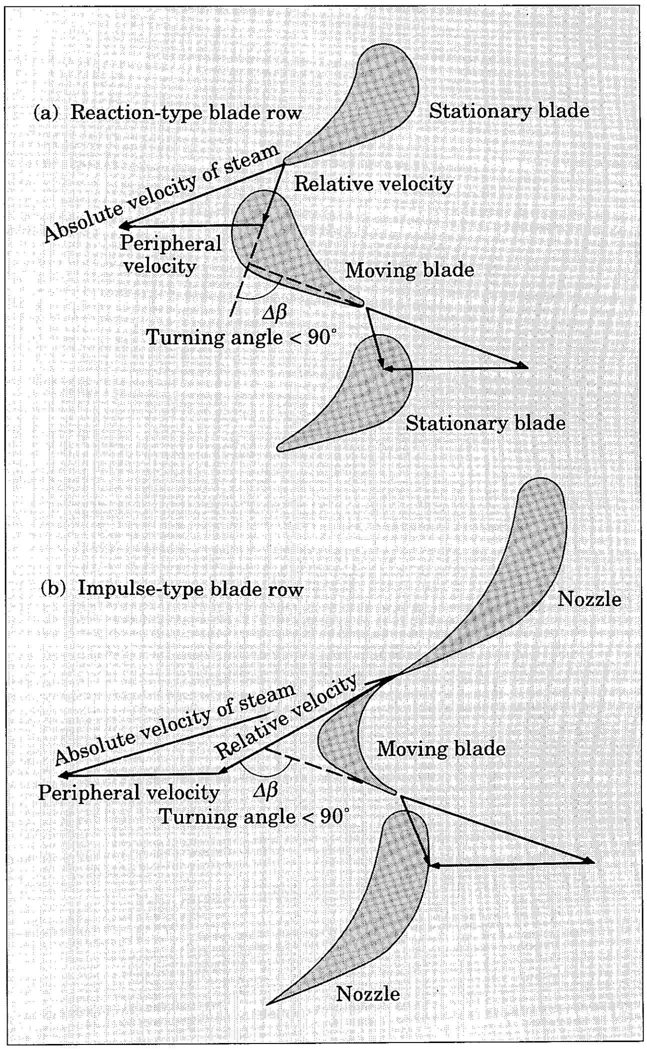
3.3 Geothermal turbine rotor without a center bore

Because the rotor of this turbine has the longest 658mm (25.9 in.) low pressure blades for a geothermal turbine, the diameter of the rotor is quite large. Stress in the center of the rotor increases almost to the allowable limit. To reduce this stress and to enhance safety against brittle fracture, the rotor of this geothermal turbine is not provided with a center bore passing through the center of the shaft.

As generally known, the maximum centrifugal stress (stress in the rotor center) of a rotor without a center bore is one-half that of a rotor with a center bore (see Fig. 9).

The allowable limit of defect dimension (the size of the defects in the rotor formed during steelmaking) of a rotor without a center bore is about five times higher than that of a rotor with a center bore, and about seven times when calculated in terms of an equivalent defect dimension (see Fig. 10).

Fig.13 Reaction-type and impulse-type blade rows



4. Fourth-Generation Skid Mount Type Geothermal Turbine

Table 1 shows the delivery history of Fuji Electric's medium capacity geothermal turbines.

Past deliveries of turbines have been mainly to 60Hz region such as the United States and the Philippines. These power plants are operating satisfactorily but the market for the development of geothermal wells has been fully saturated. In the future, 50Hz regions such as Indonesia and Africa are expected to be a promising market for geothermal power plants. To satisfy this situation, Fuji Electric has developed the fourth-generation a skid-mount type of compact geothermal turbine for 50Hz use.

The developmental concepts are as follows:

(1) a single flow and top exhaust 50Hz-20MW turbine
(2) a more compact, skid-type turbine
(3) handling a wide range of main steam pressures
(4) achieving compactness through the use of a stiff rotor

Figure 11 shows a sectional view of the turbine developed based on the above concepts.

Figure 12 shows the full view of a conventional 60Hz-20MW turbine as well as a newly developed 50Hz-20MW turbine, for comparison.

The overall length of the turbine could be substantially reduced by the adoption of a stiff rotor, which results in a remarkable reduction in bearing span. With regard to scaling and corrosion inherent in a geothermal turbine, the same considerations described in the large-capacity geothermal turbine are paid during designing. For the whole turbine unit, the installation area was reduced by 56% and the weight by 58%, resulting in facilitated installation and transportation.

5. Characteristics of Fuji Electric's Geothermal Turbine

The most serious problems in designing a geothermal turbine are corrosion and wetness of steam. Turbine materials are corroded by hydrogen sulfide and chlorine contained in geothermal steam and scraped by steam flow, leading to a reduction in thickness. Furthermore, fatigue strength of the materials decreases remarkably due to such corrosive contents as hydrogen sulfide and chlorine. In a corrosive atmosphere, stress corrosion cracking (SCC) sometimes occurs in materials with high tensile strength, such as used for rotor and blade. Any of the above can lead to the break of material pieces at a lower braking stress level than in normal air temperatures.

Fig.14 Embedding of integral shroud blades

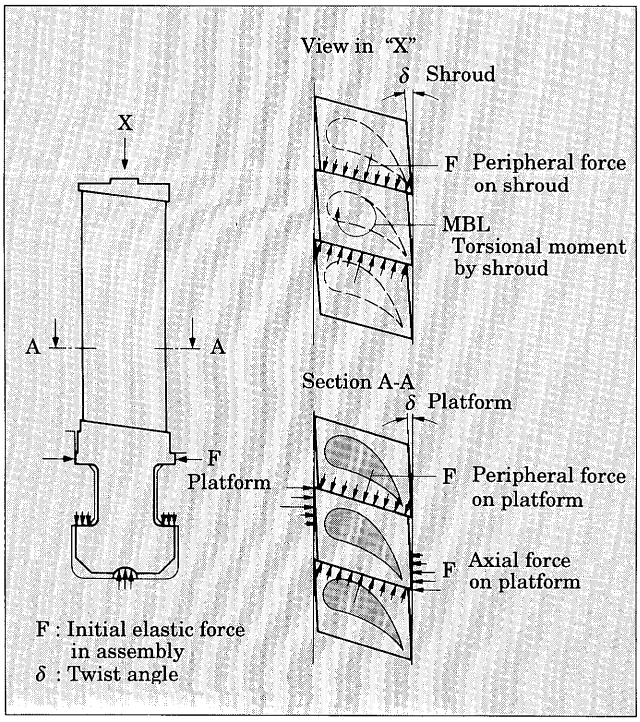


Fig.15 Vibrating stress of a blade during operation

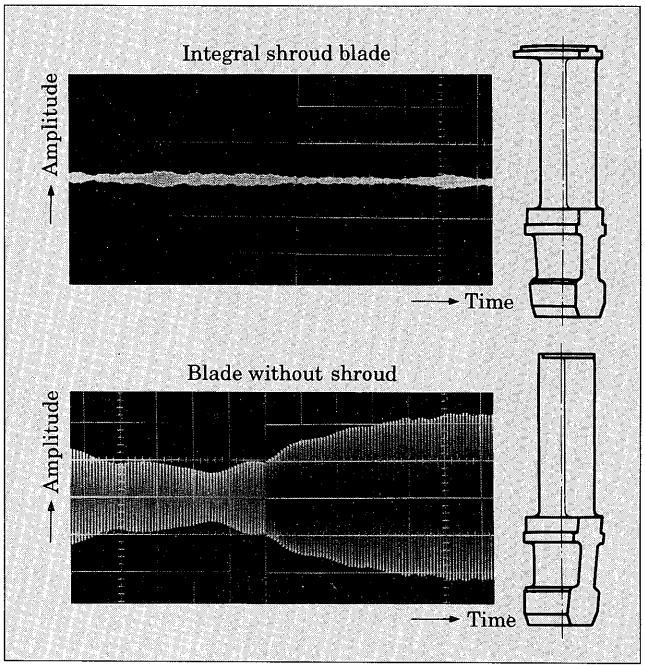
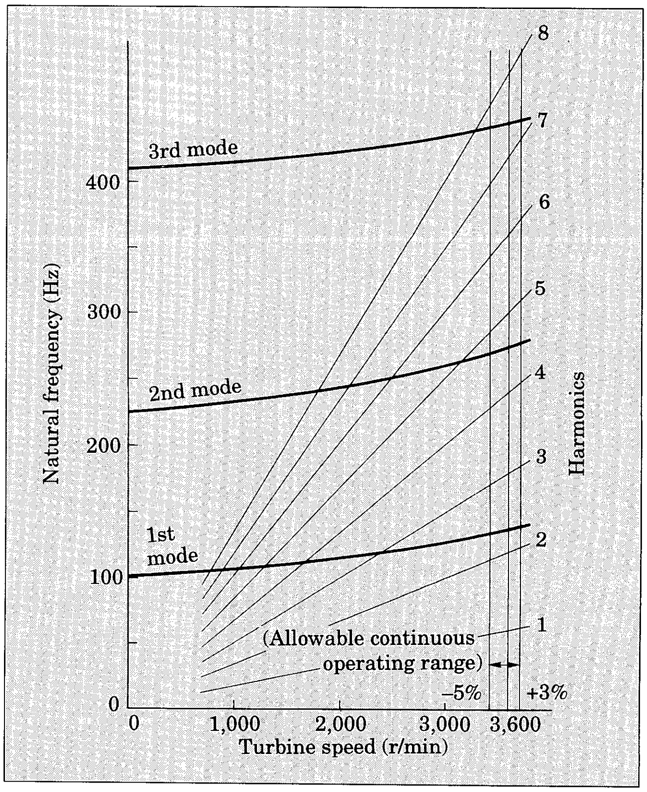


Fig.16 Campbell diagram of 658mm low-pressure, last-stage moving blade



Since the inlet steam of a geothermal turbine is in a saturated state, steam throughout the turbine becomes a mixture of vapor and liquid. This wetness of steam decreases turbine performance. In addition, water drops produced during the expansion process of steam can strike against the moving blades and erode them (erosion). There are also other problems, such as impurities contained in geothermal steam.

Because the content of impurities such as silica and iron ions in geothermal steam is 50 to 100 times as that in conventional turbine steam, scales are produced, clogging the steam passage. In addition solid particles in the steam erode the blades (solid particle erosion or SPE). Characteristics of Fuji Electric's conventional steam turbines and countermeasures against the problems of geothermal turbines mentioned above will be described below.

5.1 Reaction turbine

Fuji Electric's geothermal turbines adopt reaction-type blade rows in all stages. In reaction type blade rows, steam expands evenly in both the stationary blades (or nozzles) and moving blades (blades). The absolute velocity of the steam in the reaction-type blade rows is about one-half that of impulse-type blade rows, in which steam expands only in the nozzles (see Fig. 13).

As a result, the velocity of solid particles transported by the flow of steam decreases accordingly. Since the extent of SPE is, in general, proportional to the cube of the speed of the solid particles, reaction blades are more resistant against SPE than impulse blades.

5.2 Integral shroud blades

All blades, except long blades in the low pressure section (low pressure blade), are integral shroud blades machined from one block of material.

In contrast to the rivetting shroud, there is no residual stress caused in caulking tenons for shroud ring. As a result, there is no likelihood of stress corrosion cracking.

Fuji Electric's integral shroud blades, when embedded in the rotor, are constructed so that they form rings in the outer periphery (shroud) and in the inner periphery (platform). Peripheral pitches of blades are designed a little larger than geometrical pitches so that surface pressure (compression stress) appears on each of the contact surfaces of the platform and shroud of the adjoining blades when embedded. Thus, the blades are given elastic torsion (see Fig. 14). Since the blades are embedded in this manner, no gap can be produced between the adjoining blades under any operating conditions. Since the adjoining blades are always in contact with the platforms and shrouds, high vibration damping effect is produced due to dry friction. Fig. 15 shows the vibrating stress (alternating stress) of a blade measured in an actual turbine. As seen in the diagram, the alternating stress of an integral shroud blade is small, showing a high damping effect by the shroud.

5.3 Free-standing low-pressure blades

To cope with steam expansion, long low-pressure blades are used in the last two (2) or three (3) stages of the condensing turbine. Low pressure blades have strength problems, such as a high degree of centrifugal stress of the blades themselves and a large amount of

Fig.17 Drainage with drain catchers

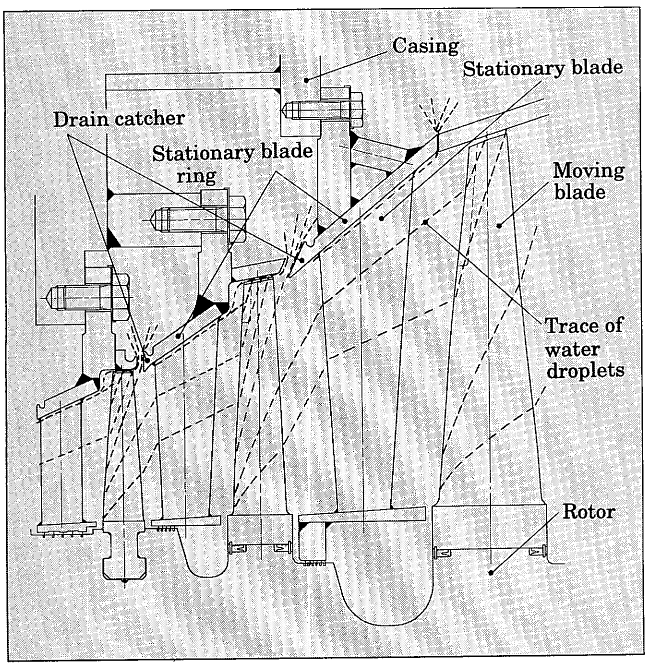


Fig.18 Effect of axial clearance of blade row and trailing edge thickness on erosion

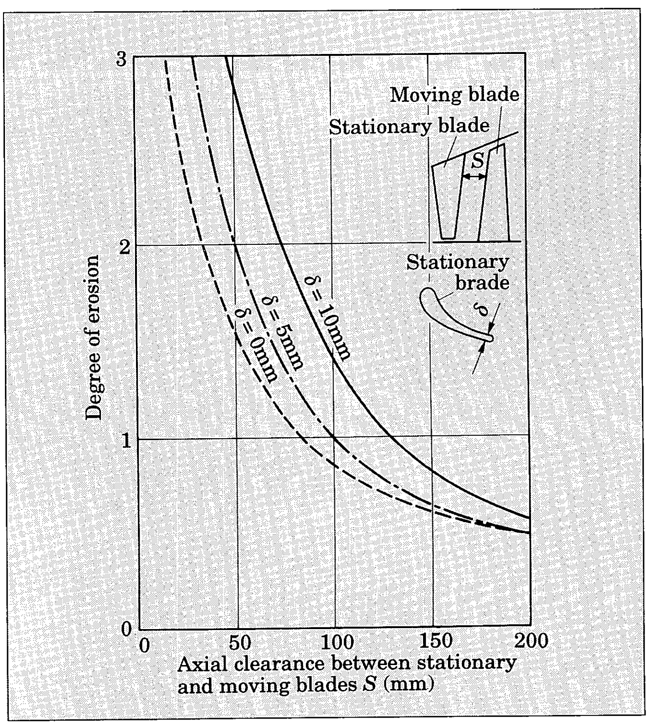


Fig.19 658mm (25.9in) last stage of moving blade

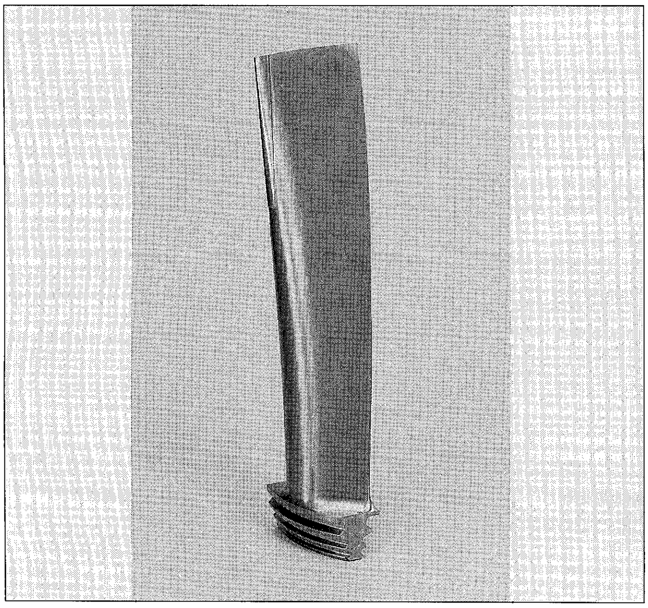
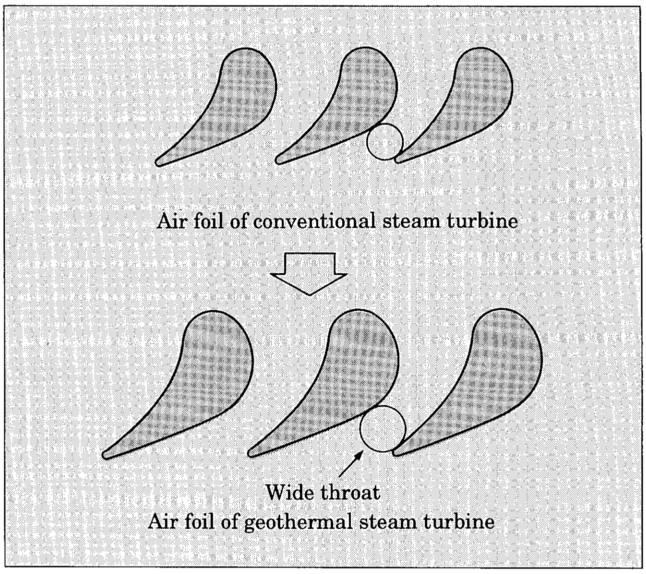


Fig.20 Wide throat



stress by steam because of their long length. In addition, they have difficulty avoiding forced excitation having integral multiples of rotational frequency (harmonics) because of their low natural frequency.

Fuji Electric adopts free-standing low-pressure blades without any additions like shrouds or lacing wire to the airfoil.

Corrosive materials do not accumulate on the blades because there are no projections on the airfoil. Stress concentration does not occur because there are no concave parts on the airfoil. These characteristics are particularly essential for stress corrosion cracking (SCC).

The vibration mode of the blades is simple as there are no additions, like shrouds or lacing wire (see Fig. 16). As a result, this design achieves ample margin in avoiding harmonic resonance at the rotational speed frequency. In addition, safe operation of the turbine unit within the wide range of frequency fluctuation, –5% to +3% of rated frequency, is possible.

Steam excitation at random frequencies caused by turbulent steam flow under extreme low load has very little effect on the blades because blade stress is kept at sufficiently low levels by adopting a long chord profile.

5.4 Drum type rotor

A solidly forged drum-type rotor having no deep notch is adopted for Fuji Electric's geothermal turbine. This type of rotor has no place for the production of high stress due to stress concentration. It is also contoured so that corrosive materials cannot easily accumulate. These two factors make the rotor safe from SCC.

5.5 Countermeasures against erosion

(1) Drainage system

Drain catchers are provided at the stationary blade rings of low pressure stages where wetness steam is high (see Fig. 17). Since the pressure of the chambers partitioned by the stationary blade rings and the casing is lower than that of the stages, moisture carried toward the casing by the centrifugal force of the moving blades is captured by the drain catchers and lead into the condenser. Thus, since the wetness in the stages decreases, erosion is moderated and turbine efficiency increases.

(2) Dispersion of water drops and reduction of their impact on blades due to acceleration

Moisture captured by the stationary blades turns into a film of water on the surface of the airfoils. This film is shed from the trailing edges of the blades and transported again as water drops by the flow of steam. Because large water drops created as above process can erode the moving blades, Fuji Electric has decreased the thickness of the trailing edges in order to reduce the size of the water drops. In addition, the gap between the stationary and moving blades has been widened so that the water drops can be dispersed and accelerated to reduce the impact caused by its collision with the moving blades. As a result, erosion is noticeably reduced. (see Fig. 18).

(3) Stellite shield

The tips of the moving blades of the last two stages are shielded with stellite plate attached by silver soldering (see Fig. 19). Stellite is about 1.5 times as hard and twice as resistant to erosion as base metal. Because it is silver soldering, residual stress is not produced and there is no possibility of SCC. Furthermore, stellite chips never peel off during operation due to long years of improvement in soldering techniques.

5.6 Countermeasures for corrosion

(1) Selection of materials and determination of design stress for a corrosive environment

In order to examine the decrease in the strength of materials in a corrosive atmosphere, a simulation in laboratory using a corrosive solution and a material tests were performed. The material tests used steam and condensed water from various geothermal sites around the world.

On the basis of the simulation results and tests, materials suitable for a geothermal turbine are selected and design stress is reduced. CrMoV material containing a small amount of Ni is adopted for a turbine rotor in place of material containing about 3% of Ni, which is used for a conventional steam turbine. In designing the blade, the dynamic stress is kept at a sufficiently lower value as compared with the design stress of a conventional steam turbine. In addition, by taking into consideration stress concentration, safety from SCC is secured in static stress design.

(2) Stainless steel overlay on the stationary blade holder

Structures such as casings are designed to include a large allowance for corrosion. The inner surface of a stationary blade holder is overlaid with stainless steel in a sufficient thickness to prevent the sealing fins embedded in the slots of the holder from falling off due to corrosion.

5.7 Countermeasures for scales

In a geothermal steam turbine as compared with a conventional steam turbine, scales accumulate more easily on the blade surface which composes steam flow passage, which can lead to a higher rate of clogs in the passage. If the steam flow passages of the blade row are clogged, inlet pressure of a blade row as well as differential pressure through the blades increase. As a result, steam mass flow rate decreases under the same steam condition, which results in decrease in output, and stress on the blades increases. In designing a geothermal turbine, much more scaling is taken into consideration than when designing a conventional steam turbine. As described in the preceding section, by keeping the design stress smaller, the size of the blades increases and the throat area (minimum channel area) also increases (see Fig. 20). Thus, even if scaling occurs, its effect on the flow of steam will be minimal and there will be a reduced possibility of a decrease in output caused by a rise in pressure in the stages.

6. Conclusion

There has been a strong demand for high performance and reliability in geothermal steam turbines. But in the future, there will be an even stronger demand for a reduction in the on-site installation period and for facilitated operation as well as easy maintenance.

Fuji Electric is determined to do its very best to utilize geothermal resources by developing new structures and new technology for geothermal steam turbines.