Titanium 50-inch and 60-inch Last-stage Blades for Steam Turbines

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OVERVIEW: Hitachi has developed 3,600 r/min 50-inch blades and 3,000 r/min 60-inch blades as last-stage buckets for steam turbines with some of the largest annulus areas in the world. Adopting these blades for use in a 1,000-MW class steam turbine provides benefits that include improving turbine efficiency in relative terms by approximately 2.5% over that of steam turbines using 40/48-inch last-stage buckets, and increasing reheat steam temperature from 600°C to 620°C. In response to the problem of supersonic inflow at the tips of the buckets, supersonic turbine blades were developed to reduce loss, and the fluid performance of these blades was verified through cascade tunnel testing. In addition, a titanium alloy with a high specific strength was used to keep the centrifugal stresses in both blade and rotor within allowable limits. The 50-inch blades that were developed will be used in the 1,050-MW ultra-supercritical pressure steam turbines in units No. 9 and No. 10 at Korea Western Power Co., Ltd.'s Tae-An Thermal power plant.

INTRODUCTION

STEAM turbines are used in various types of power generation including coal-fired power generation, gas turbine combined-cycle power generation, nuclear power generation, and other power generation systems. Together, they provide the world with more than 60% of its electric power. The world's demand for electric power will continue increasing as the population grows and standards of living improve in developing economies, with demand predicted to reach approximately 1.5 times that of 2009 in the year 2030, and approximately 2.1 in the year 2050[(1)]. As a result, along with the expanded use of renewable energy, there is also a demand for increases in the amount of electric power generated by steam turbines. In particular, coal-fired power generation is important because coal reserves are plentiful and there is not much imbalance in amounts from region to region, so coal-fired power generation can be effectively utilized.

On the other hand, from the perspective of environmental compliance, it is necessary to improve the efficiency of steam turbines in order to reduce carbon dioxide (CO_2) emissions. The average gross thermal efficiency of the world's coal-fired power plants is approximately 33% (lower heating value standard, 2009), and by replacing the turbines in these plants with Hitachi's new ultra-supercritical pressure[*1] steam turbines with efficiency greater than 45%, it will be possible to reduce CO_2 emissions by more than 30%.

Fig. 1—3,600 r/min 50-inch Last-stage Buckets.
With an annulus area among the largest in the world[*2]*, turbine efficiency is improved by reducing wasted kinetic energy.*

*1 Steam conditions with temperature at 593°C or higher and pressure at 24.1 MPa or higher.

*2 Based on research into publically available information as conducted by Hitachi, Ltd. Current as of September 2012.

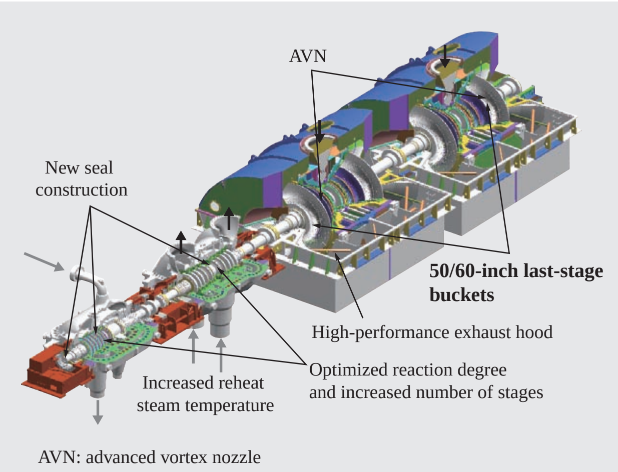


Fig. 2—Measures for Improving Efficiency of 1,000-MW Class Steam Turbines.
Efficiency is improved for steam condition, blades, seals, and exhaust hoods. In particular, efficiency is improved a great deal by the lengthening of the last-stage buckets.

This article discusses technologies used to increase the efficiency of steam turbines, and in particular, the development of titanium 50-inch (see Fig. 1) and 60-inch last-stage blades.

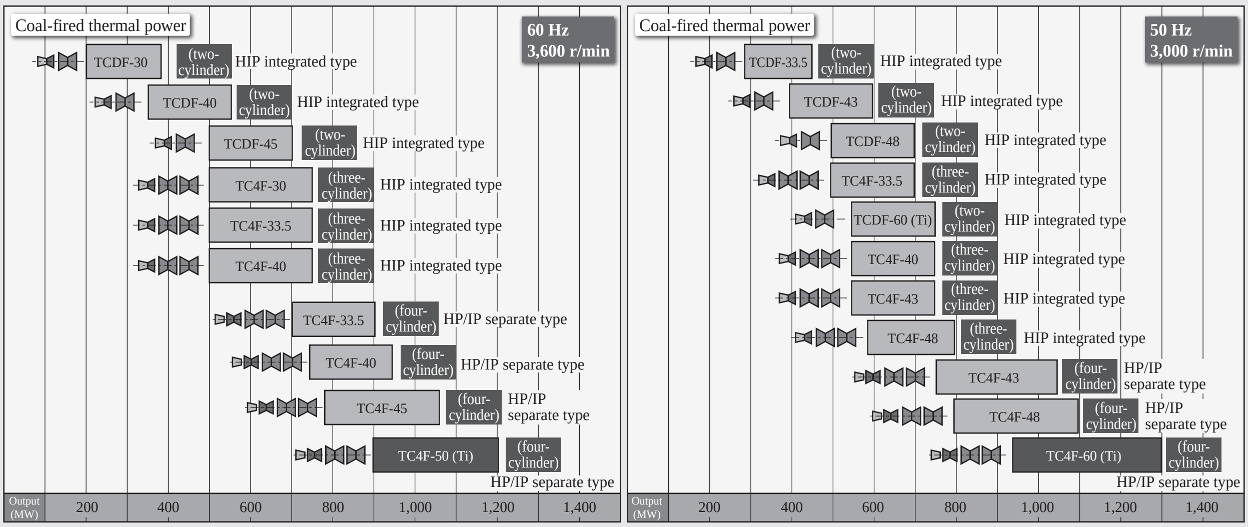
CHARACTERISTICS OF 50/60-INCH LAST-STAGE BLADES

Measures taken to improve the efficiency of a 1,000-MW class steam turbine include, but are not limited to, lengthening the last-stage buckets (moving blade), increasing the reheat steam temperature, optimizing reaction degree, increasing the number of stages, adopting a new seal construction that reduces gaps, developing an advanced vortex nozzle (AVN) (nozzle is a stationary blade), and improving the pressure recovery effect of the exhaust hood (see Fig. 2).

The last-stage blade Hitachi developed is a 50-inch blade with one of the largest annulus areas in the world (the area of the blade's circular ring part, where the flow passes through), for use in 3,600 r/min turbines, as well as a 60-inch blade with a similar design for 3,000 r/min turbines (see Table 1)[2]. Although some of the kinetic energy emitted from the last-stage is used by the exhaust diffuser to recover pressure, most of it cannot be extracted as power, and is lost. By increasing the size of the annulus area, decreasing the axial velocity of the last-stage outlet, and reducing

TABLE 1. 50/60-inch Last-stage Blade Specifications
The annulus areas are among the largest in the world, and a titanium alloy is used to reduce centrifugal stress.

Parameter	50 inch	60 inch
Rotational speed	3,600 r/min	3,000 r/min
Blade length	1,250 mm	1,500 mm
Annulus area	11.5 m^2	16.5 m^2
Boss ratio (blade inner diameter/ blade outer diameter)	0.40	
Blade tip speed	786 m/s	
Blade material	Ti-6Al-4V alloy	



TC4F-50: TC (tandem compound) high-pressure, intermediate-pressure, and low-pressure turbines are all connected along a single axis. 4F means the number of last-stage flows, with "4F" meaning "four-flow" and "DF" meaning "two-flow." -50 = length of last-stage buckets. Ti: titanium
HIP: high and intermediate pressure turbine HP: high-pressure turbine IP: intermediate pressure turbine

Fig. 3—Output Lineup of Steam Turbines for Use in Coal-fired Power Generation, Based on Turbine Type and Last-stage Blade Length.
These 50-inch and 60-inch blades are used in 1,000-MW class output steam turbines with low-pressure turbines and two cylinders (four flows).

the emitted kinetic energy, it is possible to improve efficiency. The developed blades have annulus areas approximately 1.4 times as large as the annulus areas of previous 40-inch and 48-inch blades, and this greatly contributes to the improved efficiency.

The 50-inch and 60-inch blades that were developed are used in 3,600 r/min and 3,000 r/min 1,000-MW class steam turbines, respectively. Low-pressure turbines are two-cylinder/four-flow designs, with a four-cylinder construction shared by high-pressure and intermediate-pressure turbines (see Fig. 2). This completes a wide lineup of steam turbines for coal-fired power generation, ranging from 200 to 1,300-MW (see Fig. 3).

When the aforementioned efficiency improvement measures are taken and the reheat steam temperature is increased to 620°C in a 1,000-MW class steam turbine using the developed last-stage buckets, turbine efficiency can be improved approximately 2.5% relative to a steam turbine with a reheat steam temperature of 600°C using 40/48-inch last-stage buckets.

FLUID PERFORMANCE DESIGN

The reduction of loss in supersonic inflow is an aerodynamic issue affecting the development of 50-inch and 60-inch-long blades. As blades grow longer, the circumferential velocity increases in the tips of the buckets, causing the relative inflow speed to go supersonic. Supersonic inflow causes shockwaves upstream in the buckets, which in turn interfere with the boundary layer at the blade surface, possibly resulting in loss.

The inflow Mach number was reduced, and a supersonic turbine blade was developed in order to reduce loss caused by supersonic inflow (see Fig. 4).

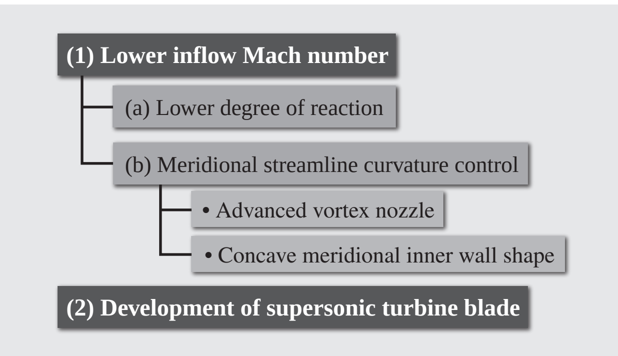


Fig. 4—Measures to Reduce Loss Caused by Supersonic Inflow on Bucket Tips.
Shockwave loss was reduced by lowering the inflow Mach number and developing a supersonic turbine blade.

Reduction in Inflow Mach Number

In order to reduce the inflow Mach number, lowering the reaction degree (bucket load/stage load) was considered first. With a lower reaction degree, the nozzle outlet pressure is reduced as the nozzle outflow speed is increased, resulting in a lower relative inflow speed for the buckets.

At the nozzle outlet, however, this balances out with the centrifugal force caused by the swirl flow with its convex curvature, causing the pressure to increase as it moves closer to the outer circumference (see Fig. 5). Therefore, to decrease the nozzle outlet pressure at the outer circumference, it is necessary to reduce the pressure gradient in the radial direction.

For this reason, it is decided to develop technology that would control streamline curvature on the meridional plane, or in other words, on the plane including the turbine's axis of rotation (see Fig. 6). Specifically, by inducing a meridional streamline at the nozzle outlet with a concave curvature that is reversed from the convex curvature of the swirl flow, the pressure on the outer circumference side was decreased while the pressure on the inner circumference side was increased (see Fig. 5). The concave meridional streamline was introduced using the concave meridional inner wall (see Fig. 6) and the advanced vortex nozzle (see Fig. 7).

The advanced vortex nozzle is a nozzle tilted in the circumferential direction with the blade's

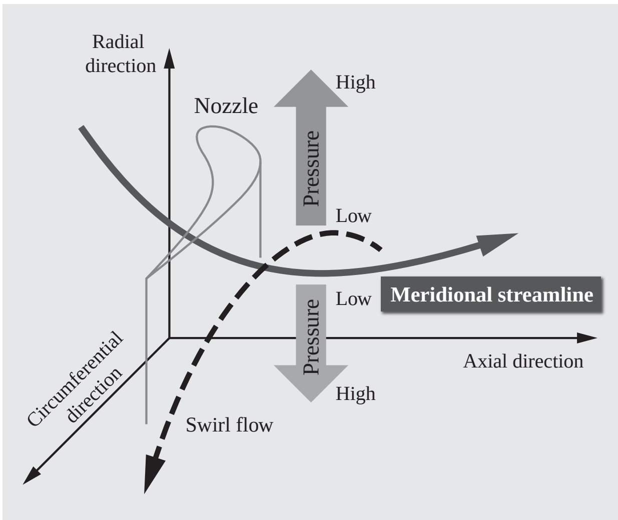


Fig. 5—Relationship between Meridional Streamline and Radial Direction Pressure Gradient.
By introducing a meridional streamline curvature with a concave shape to the nozzle outlet, a negative pressure gradient is induced in the radial direction, increasing the pressure in the inner circumference of the nozzle outlet while reducing the nozzle outflow Mach number.

pressure surface facing the inner circumference. Although with a straight stacking nozzle, a vortex is only generated around an axis in the radial direction, with an advanced vortex nozzle, it is curved in the circumferential direction, and also induces a vortex in the meridional plane perpendicular to the circumferential direction (see Fig. 7). As shown in Fig. 6, this meridional vortex forms a meridional streamline with a concave curvature between the nozzle and the buckets. The concave meridional inner wall introduces a concave curvature to the streamline near the inner circumference.

The advanced vortex nozzle and meridional inner wall shape were optimally designed using three-dimensional stage turbulent flow analysis. The Mach number distribution resulting from this analysis is shown in Fig. 6. The relative Mach number of the buckets tip's inflow is reduced to 1.26, which is low enough that a strong upstream shockwave is not generated. Also, when the reaction of the entire stage is reduced, although the outflow Mach number on the nozzle's inner circumference side exceeds 1.6, meridional streamline curvature control technology makes it possible to only decrease the pressure on the outer circumference side while increasing the pressure on the inner circumference side, so the outflow Mach number on the inner circumference side can be lowered to approximately 1.4.

Development of Supersonic Turbine Blades

A supersonic turbine blade was developed that can inhibit shockwave loss[3]. With these newly developed long steam turbine blades, the supersonic inflow is accelerated between blades and outflows at an even higher supersonic speed, which is something not even the latest jet engines can do. For this reason, Hitachi used a numerical turbulence analysis method[4] that it developed to optimize the shape of the supersonic turbine blade while considering the characteristics of the flow passage area and the long steam turbine blades, and verified fluid performance with supersonic cascade tunnel testing[2].

These blades offer the following three major characteristics:

(1) The flow path between blades is the expanding flow path with a minimal flow path area part (throat) at the inlet.

(2) The blade thickness increases gradually at the leading edge.

(3) Curvature is low on the upstream side of the blade pressure surface.

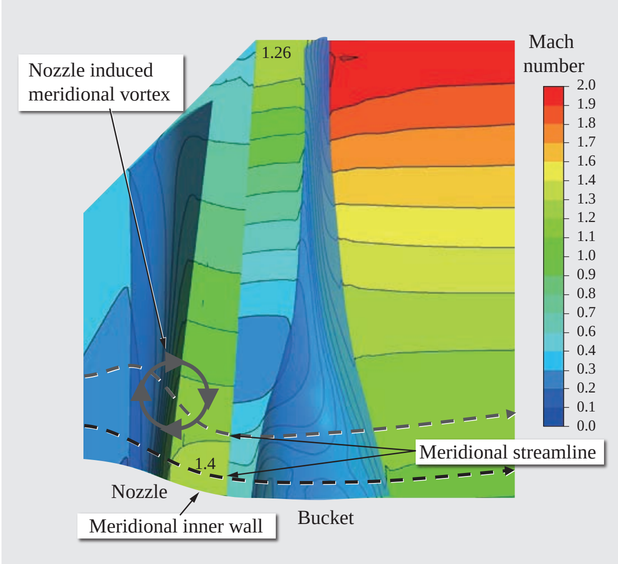


Fig. 6—Mach Number Distribution in Meridional Plane through Three-dimensional Stage Turbulent Flow Analysis.
The nozzle part is the Mach number, and the bucket part is the relative Mach number. The vortex induced by the advanced vortex nozzle and the concave inner wall shape induce a meridional streamline with a concave curvature at the nozzle outlet, keeping the relative Mach number low for the nozzle outflow and the bucket inflow.

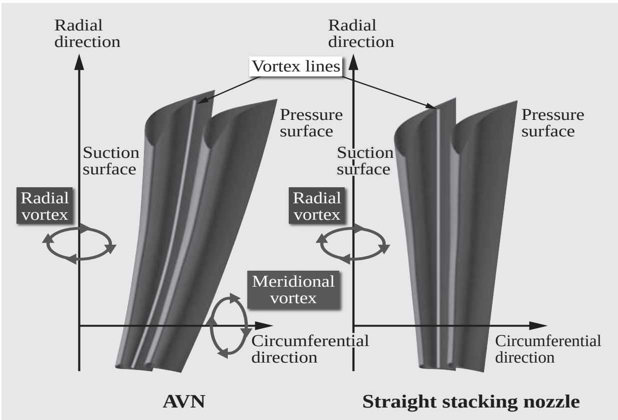


Fig. 7—Comparison between Advanced Vortex Nozzle and Straight Stacking Nozzle.
The advanced vortex nozzle is a nozzle with the blade's pressure surface slanted in the circumferential direction towards the inner circumference. This curve induces a vortex on the meridional plane, controlling the meridional streamline and adjusting the Mach number.

Characteristic (1) causes the supersonic flow's accelerated expansion to be smooth between the blade's flow paths and weakens the trailing edge shockwave, while characteristics (2) and (3) weaken the upstream shockwave and equalize the flow at the inlet throat, which makes it possible to satisfy the mass flow rate design specifications.

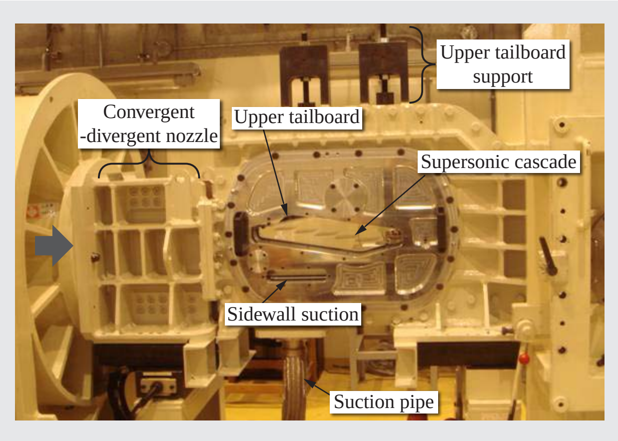


Fig. 8—Supersonic Cascade Test Section Assembly.
The supersonic inflow Mach number was set with a convergent-divergent nozzle, and the outflow Mach number was adjusted via the upper tailboard angle. There were seven blades, the aspect ratio was 1.07, two-dimensionality of the flow was secured, and sidewall suction improved the periodicity of the cascade flow.

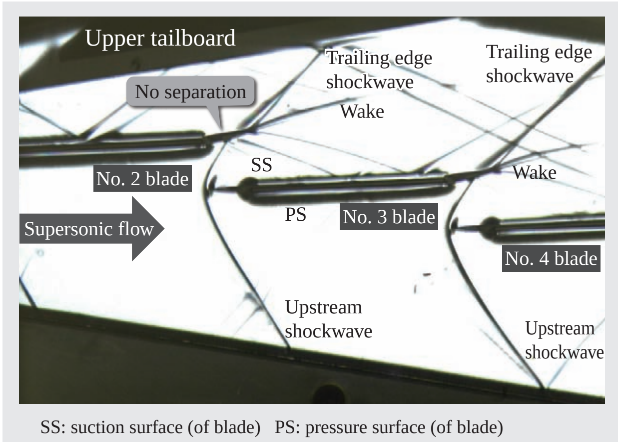


Fig. 9—Schlieren Visualization Photograph of Supersonic Cascade Testing.
Both the upstream shockwave and trailing edge shockwave are weak, skewed shockwaves, and it was confirmed that interference with the upstream shockwave does not cause the boundary of the blade surface to detach.

During the cascade test, the tested section was affixed to the Kyushu University supersonic wind tunnel (see Fig. 8). This is an intermittent wind tunnel, and air was used as the working fluid. A convergent-divergent nozzle was used to set the Mach number of the inlet's supersonic flow, and the angle of the upper tailboard was changed to adjust the pressure ratio. Suction from the downward sidewall to the sidewall boundary layer improved the periodicity of the cascade flow. The seven test blades were 1/5th the scale of production blades, the aspect ratio was 1.07, and flow two-dimensionality was secured. The Reynolds number based on the blade's chord length was the same 2.3×10^6 as for production blades.

These cascade tunnel tests successfully verified that the newly developed supersonic turbine blades satisfy the design conditions and are high-performance. A Schlieren photograph used in measurement during the testing is shown in Fig. 9. These are test results with an inflow Mach number of 1.26 and an isentropic outflow Mach number of 2.1. Since the effects of the reflected shockwave on the sidewall are small, the flow between the 2nd and 4th blades from upstream was noted. The black shadow around the blades is strain from the construction of the acrylic sidewall channel. Regardless of the supersonic inflow, no strong shockwave is generated, which indicates the boundary layer of the blade surface does not separate due to interference with the shockwave.

Fig. 10 shows a diagram combining the density gradient distribution of the numerical turbulence analysis results with the Schlieren photograph of the cascade tunnel testing. The analysis clearly captured the shockwaves, and as the upstream shockwave, the trailing edge shockwave, and the reflected shockwaves on each blade surface as well as the blade wake position closely matched the test results, this verifies the methods used to design the supersonic turbine blades as well as the accuracy of numerical turbulence analysis.

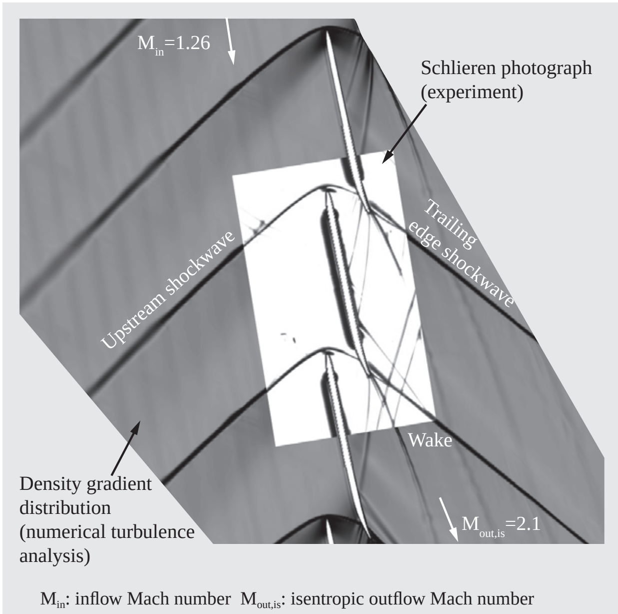


Fig. 10—Comparison between Supersonic Turbine Blade Experiment and Numerical Turbulent Flow Analysis.
The upstream shockwave, trailing edge shockwave, and reflected shockwave on each blade surface, as well as the position of the blade wake, all closely matched experiment results, validating the accuracy of numerical turbulence analysis.

STRUCTURAL RELIABILITY DESIGN

Strength Design

In order to keep the centrifugal stress, which increased as a result of blade lengthening, within the allowable stress, a titanium alloy with a high specific strength was used. The titanium alloy has a low density equivalent to approximately 56% that of steel, and this also means that the stress affecting the rotor can be reduced. The titanium alloy also offers superior characteristics when compared to steel in terms of corrosion resistance and stress corrosion cracking in the last-stage buckets during operation in wet steam.

The blade's stress distribution based on three-dimensional non-linear finite element method analysis, with consideration given to large deformation and contact, is shown in Fig. 11. It was confirmed that neither blade nor blade root attachments exceeded the allowable stress. In particular, the balance between cross-sectional average stress, contact surface pressure, and local stress was adjusted between the blade root attachments and the blade grooves on the rotor side, in order to create a design that offers sufficient strength reserve against both high-cycle and low-cycle fatigue. The benchmarks for high-cycle fatigue strength and low-cycle fatigue strength were confirmed through fatigue testing in a corrosive environment and component testing that simulated the shape of the blade root attachments and the bucket groove.

For the tip covers, strength versus fretting wear and abrasion of the contact surface was secured while the tip covers were made slimmer to reduce weight, as the stress on blade and rotor was reduced. Test methods were formulated to simulate the dynamic characteristics of the cover contact part(5), and the contact normal force limit was identified such that fretting wear does not occur even when the vibration tangential force is strong. The vibration tangential force was designed to be equal to or greater than the strength whereby a sufficient damping effect is achieved, and equal to or less than the strength where excessive abrasion would occur.

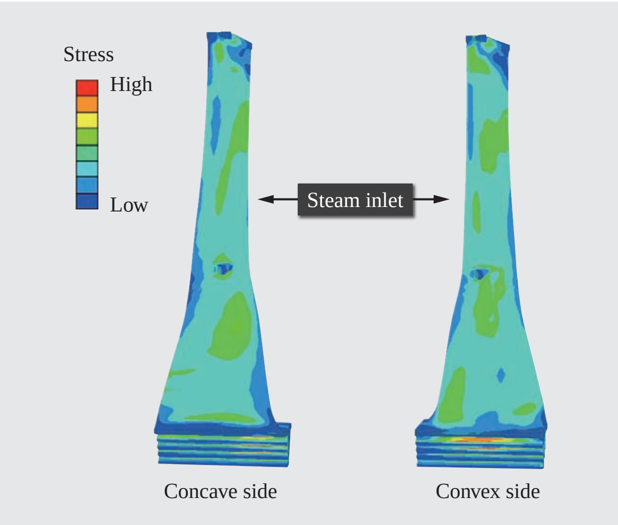


Fig. 11—Blade Stress Distribution (Finite Element Method).
Centrifugal stress is held underneath the allowable value due to the use of a titanium alloy with a high specific strength.

Vibration Design

Although with the longer blades, each single blade's rigidity is reduced, by adopting a continuous cover blade (CCB) construction whereby the cover part and the tie-boss at the height between the blades are in continuous contact, it is possible to increase the rigidity of the single ring full-circumference blades, avoiding resonance in all low-order modes near the rated rotational speed. For this reason, vibrational stress is extremely low within the allowed operating rotational speeds. Also, due to the energy dissipation mechanism of the contact connections in the CCB construction, the structural damping ratio is high, and it is possible to keep vibration stresses within allowable limits over a wide operating range.

The vibrational characteristics of the single ring full-circumference blades are such that vibration is coupled through the connection parts for all blades around the circumference. As a result, in response to a single eigenmode of a single blade, there is a eigenmode group that is referred to as a series of nodal diameter modes starting with 0, 1, 2, and so on, just as the case with disk vibration. Not all of these nodal diameter modes resonate with the exciting force in synchronization with the rotational frequency, however, and resonance only occurs when the vibrational harmonics and the nodal diameter number match (or more precisely, when the sum of or difference between the vibrational harmonics and the nodal diameter number is an integral multiple of the number of buckets). The three-nodal-diameter mode of the blade's first bending is shown in Fig. 12. The vibration mode characteristics of these types of single ring full-circumference blades were given consideration in order to avoid resonance in the design.

In addition, the amount of residual deformation after operation at 120% speed was evaluated using elasto-plastic analysis, with the cover and tie-boss rigidly connected to each other after the rated number of rotations, showing that the single ring full-

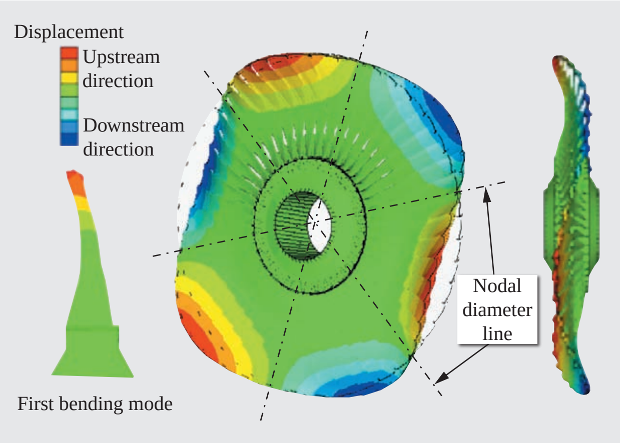


Fig. 12—Three-nodal-diameter Mode of Blade's First Bending Based on Vibration Analysis.
Rigidity is increased as single ring full-circumference blades, and resonance is avoided in all low-order modes near the rated rotational speed.

Fig. 13—Rotational Vibration Test.
Rotational vibration tests in a vacuum chamber were used to confirm that resonance is avoided.

circumference blade structure could be maintained. Increasing rigidity reduced the response to blade vibrations, and the contact angle, contact area, contact start rotational speed, and gaps at rest were determined so that the cover and tie-boss contact parts work as vibration damping mechanisms.

The results of rotational vibration tests using a vacuum chamber confirmed that resonance is avoided in all low-order modes near the rated rotational speed (see Fig. 13).

CONCLUSIONS

This article described the development of high-efficiency technology for steam turbines, in particular the development of 50-inch and 60-inch titanium last-stage blades.

By using these blades, it is possible to improve the turbine efficiency of a 1,000-MW class steam turbine that has two cylinders in the low-pressure stage. The increased annulus area means that the kinetic energy that cannot be used as power lost from the stage in a steam turbine using 40-inch or 48-inch blades, or in other words the exhaust loss, can be reduced. This results in an improved turbine efficiency of approximately 2.5% in relative terms, including the effect of the increased reheat steam temperature.

With respect to the problem of supersonic inflow at the tips due to blade lengthening, numerical turbulence analysis technology and supersonic cascade tunnel testing were used to develop supersonic turbine blades. The adoption of a titanium alloy with a high specific strength made it possible to reduce centrifugal stress on both blades and rotors, resulting in a design with sufficient reserve strength. As the blades are constructed in such a way that they are in contact with and connect to each other, rigidity and vibration damping are greatly increased due to the single ring full-circumference blade structure, and therefore resonance is avoided near the rated rotational speed.

These newly developed 50-inch blades will be used in the 1,050-MW ultra-supercritical pressure coal-fired power generation steam turbines in units No. 9 and No. 10 at Korea Western Power Company's Tae-An Thermal power plant.

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