A High-efficiency Steam Turbine Utilizing Optimized Reaction Blades — An Application to the Kwangyang Combined-cycle Power Plant of K-Power of Republic of Korea —

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OVERVIEW: In recent years, since reduction of carbon-dioxide emissions is drawing major attention, new thermal power plants — the main body of which are destined for overseas markets — demand improved thermal efficiency even in the case of steam turbines. At the same time, in regard to rotor blades (which have relatively small blade length), the role of aerodynamic loss in the secondary flow regions and in the boundary layers along the blade length becomes significant; therefore, Hitachi developed an optimized reaction blade based on a new design concept that takes such steam flow characteristics into account. Applied in the high-pressure-turbine sections of two steam turbines for combined-cycle power generators hitherto used for 50-Hz generation, these blades significantly improve the efficiency of the high-pressure turbines. The optimized reaction blades were installed in the high-pressure turbines of the Kwangyang Combined-cycle Power Plant (steam-turbine output power: 200 MW) of K-Power of Republic of Korea. It was confirmed by performance testing on actual turbines that in this first application to 60-Hz turbines, these blades significantly improve turbine efficiency in a similar manner to the 50-Hz applications so far practically implemented.

INTRODUCTION

AS regards thermal power generation in recent years, to reduce carbon-dioxide emissions and fuel consumption from the viewpoint of environmental protection, the need to improve the efficiency of power plants has been growing ever stronger. In particular, in the case of steam turbines, improvement of thermal efficiency has become vital.

Aiming to attain high efficiency, Hitachi, Ltd. has been developing rotor blades for the steam turbines of thermal power plants. As for the relatively short rotor blades (i.e. small blade height) applied in the high-

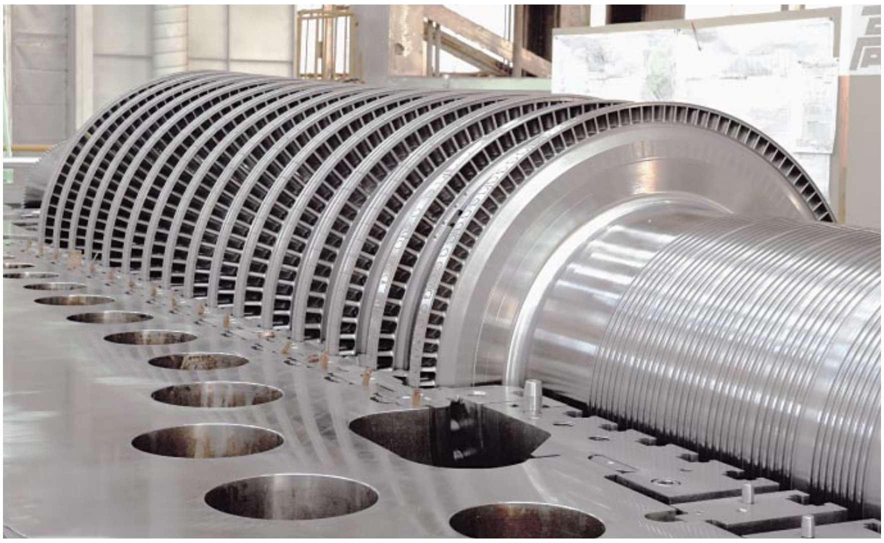

Fig. 1—High-pressure Turbine Unit of the 200-MW Steam Turbine for the Kwangyang Combined-cycle Power Plant of Republic of Korea's K-Power. The high-pressure turbine rotor is integrated in the lower half of the turbine casing, and the high-pressure turbine adopts optimized reaction blades (newly developed by Hitachi) for all turbine stages.

pressure turbine section of small and mid-class steam turbines, the proportion of aerodynamic loss (namely, in the secondary flow region and the boundary layer along the blade length) becomes bigger. It thus becomes necessary to develop a high-performance blade profile that takes into account such steam flow characteristics.

In the present work, the degree of reaction in the design of the steam path was optimized, a design of experiments for designing the blade profile of rotor blades for a high-pressure turbine was introduced, and a new kind of rotor blade with "robust" loss characteristics against inlet-angle variation was developed. This rotor blade is applied in the high-pressure section of a 200–300-MW-class steam turbine for combined-cycle power generation, and a significant improvement in efficiency was confirmed by performance tests.

Focusing on the turbine for the Kwangyang Combined-cycle Power Plant of Korea's K-Power, this report describes the newly developed optimized reaction blades (hereafter abbreviate as HX blades) for a high-pressure turbine (see Fig. 1).

DEVELOPMENT OF HX BLADES

Development Strategy

As for improving internal efficiency of high-pressure steam turbines, small root diameter and a large number of stages is effective. Accordingly, for turbines whose steam-path design adopts various measures for improving internal efficiency, optimization calculations with parameters such as stage number, blade root diameter, and root reaction are executed, and optimum points are thereby obtained (see Fig. 2). Moreover, as for this steam-path design, various loss models (e.g. profile loss and secondary loss) based on the results of flow analysis and experimental tests are incorporated. As for the rotor blades developed in the present work, the combination of stage number and root reaction that gives the highest turbine efficiency is obtained, and this result was taken as the design conditions for the developed blade.

The turbine that exploits the optimized steam path possesses a higher degree of reaction in comparison with the high- and intermediate-pressure steam turbines introduced by Hitachi up till now. The design of the new rotor blades applied in this turbine is described in the following.

The HX blade that we have newly developed has two characteristic features: first, it is applied in the high-pressure turbine section and, second, because the application profile (i.e. cross-sectional shape) is sectioned in accordance with blade height, a further optimized blade profile is applicable from the viewpoint of performance concerning each stage of the turbine.

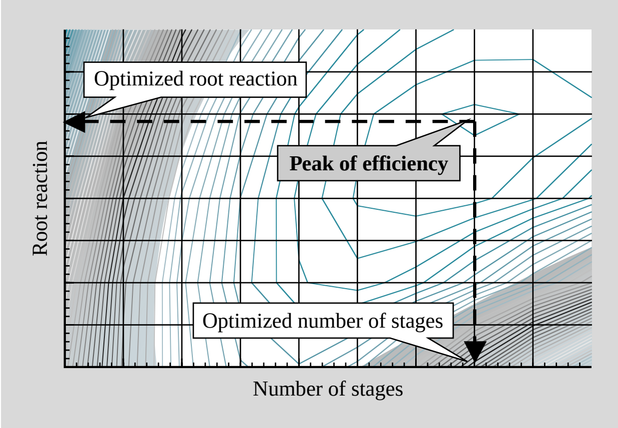

Fig. 2—Optimization Example of Steam-path Design.
The horizontal axis shows number of stages; the vertical axis shows root reaction. The contour lines represent the distribution of turbine efficiency, and it is clear that peaks of efficiency exist at certain combinations of stage number and root reaction.

The application region of each blade profile is separated into two types according to steam flow characteristics as follows.

Region 1: Blade height is small, and loss at end walls becomes dominant.

Region 2: Blade height is comparatively large, and the influence of loss at end walls is low.

Two versions of the HX blades were developed as blades optimized for the flow in each region.

Based on the highly loaded blades developed by Hitachi and applied on numerous actual turbines so far, the HX blades for region 2 are modified types that improve root reaction from the viewpoint of attaining high efficiency.

In the following, an overview of the development of the HX blades applied in region 1 is given.

Overview of Development of HX Blades

As mentioned above, in regard to the stages in which blade height is low and loss at end walls becomes dominant, the HX blades for region 1 (hereafter just HX blades) are applied.

Velocity triangles for the blade inlets are shown in Fig. 3. According to the peripheral velocity of the rotating blade, steam at the absolute velocity at the stationary-blade outlet flows into the rotor blade at the relative velocity as shown in the figure (inflow angle β_1). It is clear from Fig. 4 that the profile loss

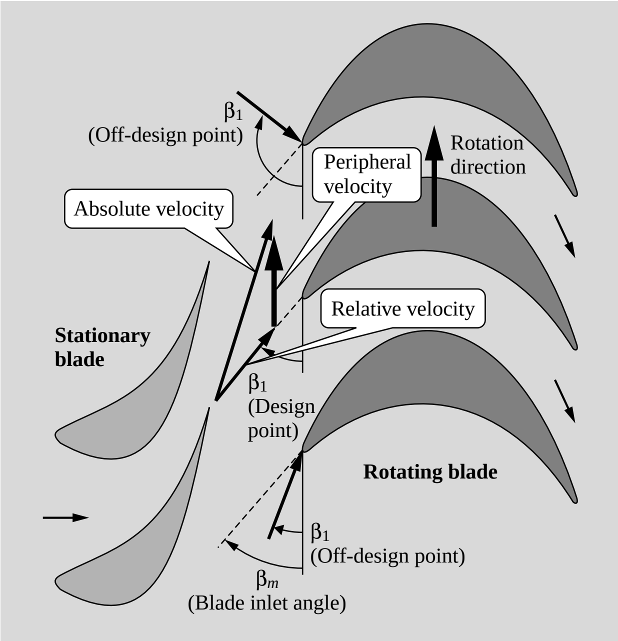

Fig. 3—Velocity Triangles.
As for conventional rotor blades, the design must match design points and blade inlet angles as much as possible.

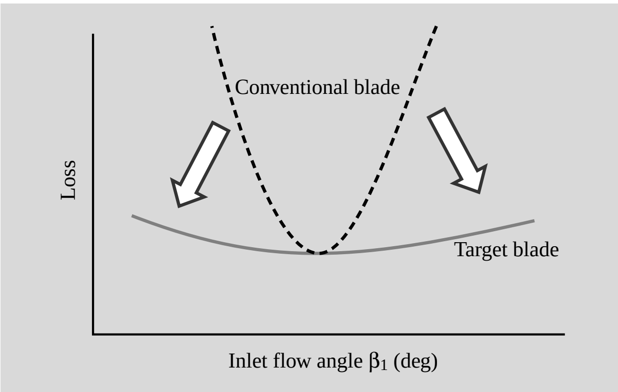

Fig. 4—Profile-loss Characteristics.
For a rotating blade with low blade height, it is necessary to develop a blade with the characteristic that its loss does not become large across a wide range of inlet flow angles.

increases as the direction of the relative velocity deviates from the inlet mechanical angle (β_m) of the rotating blade. In the case of a conventional blade profile, it is a problem that loss characteristics are particularly sensitive to inlet flow angle β_1, so a design that reduces the deviation between angles β_1 and β_m is necessary. In practice, however, the influences of the boundary layer and secondary flow must be taken into account, and it is difficult to accurately predict the relative inlet angle for a rotor blade during the design stage.

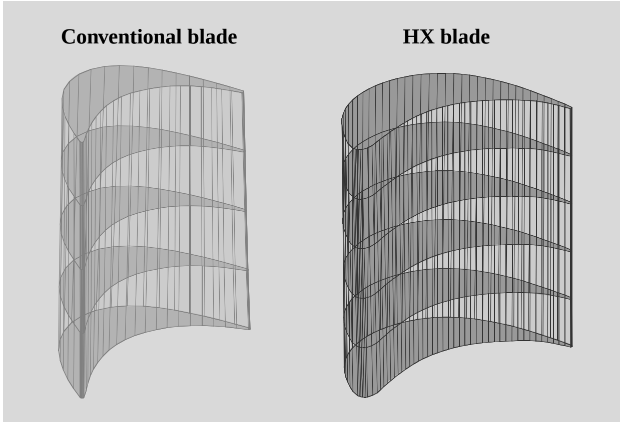

Fig. 5—Comparison of Profiles of Conventional Blade and HX Blade.
The HX blade has a blunted inlet section (i.e. a "blunted nose") in comparison with the conventional blade.

In particular, regarding region 1, since the boundary layer and secondary flow region become dominant in the direction of blade height, inlet flow angle β_1 for an actual flow is distributed across a wide range. As for a conventional blade profile, loss characteristics are sensitive to inlet flow angle, so it is necessary to develop a new rotor blade profile with the property that loss varies little even over a wide range of inlet flow angles.

Given the above requirement, in regard to the development of the HX blade, we adopted a design of experiments to develop a new blade whose loss characteristic is "robust" against variation in inlet flow angle.

The shape of the newly designed HX blade is shown alongside that of a conventional blade in Fig. 5. The design of the HX blade was optimized by "design of experiments" and CFD (computational fluid dynamics), and in comparison to the inlet region of the conventional blade, that of the HX blade is significantly blunted.

To investigate the two-dimensional blade profile loss, a two-dimensional cascade wind tunnel was used, and energy-loss coefficient was calculated from five-hole pitot-tube traverse measurements. The correlation between energy-loss coefficient ζ and inlet-flow angle β_1 is plotted in Fig. 6. The HX blade shows an approximately constant loss coefficient across a wide range of inlet-flow angles from 40° to 80°, and the level of loss coefficient is lower than that of the conventional blade for the whole range of inlet angles.

Finally, to evaluate the turbine performance in the case that the HX blades were applied to turbine stages,

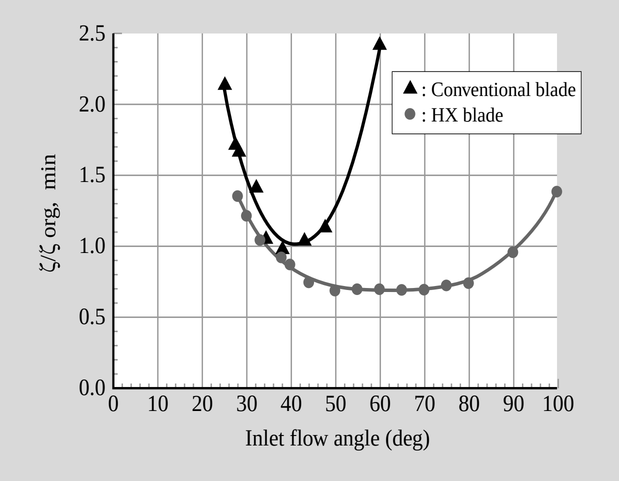

Fig. 6—Comparison of Inlet Flow Angle Characteristics of Conventional and HX Blades.
The HX blade has an approximately stable loss coefficient across a wide range of inlet flow angles, and it shows a loss coefficient at a lower level than that of the conventional blade.

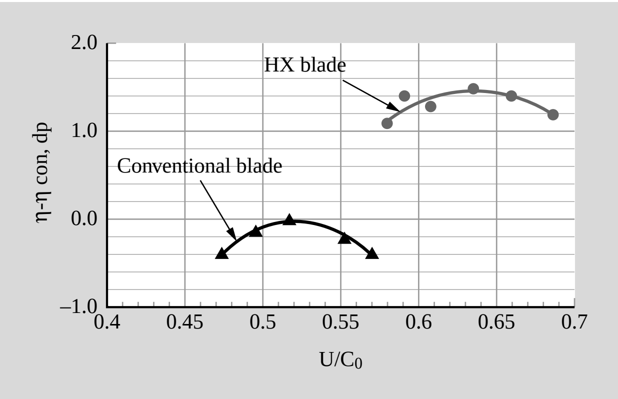

Fig. 7—Comparison of Stage Efficiency of Conventional and HX Blades.
Deviation (%) of stage efficiency at design points of conventional blade (on the vertical axis) and root-reaction ratio (on horizontal axis) is shown. The HX blades achieve an improvement in efficiency of more than 1% in comparison with the conventional blades.

model turbine tests were performed.

The turbine stage efficiencies of the HX blade and a conventional blade (obtained by a single-stage air-turbine tests) are compared in Fig. 7. It is clear from the figure that in comparison with the efficiency of the conventional blade, that of the HX blade is improved by about 1.5% at all design points. However, if excluding the influences of leakage flow (due to differences in degrees of reaction of rotary-blade edges and seal constructions in the two cases) , the HX blade improves stage efficiency by 3%, simply by changing blade configuration.

APPLICATION TO ACTUAL TURBINES

Application of HX Blade in Actual Turbines

Up till now, the HX blade developed in this work has been applied in a total of four actual steam turbines for combined-cycle power generation at three power companies (namely, one 381-MW-output-power turbine at Spalding Energy Co., Ltd. of the UK, one 250-MW turbine at the Egyptian Electricity Holding Company of Arab Republic of Egypt, and two 200-MW turbines at K-Power of Republic of Korea), and all these turbines have started commercial operation and are continuing to operate smoothly.

As one of these examples of application to an actual turbine, the 200-MW steam turbine for the Kwangyang Combined-cycle Power Plant of K-Power of Republic of Korea — the first 60-Hz turbine incorporating the

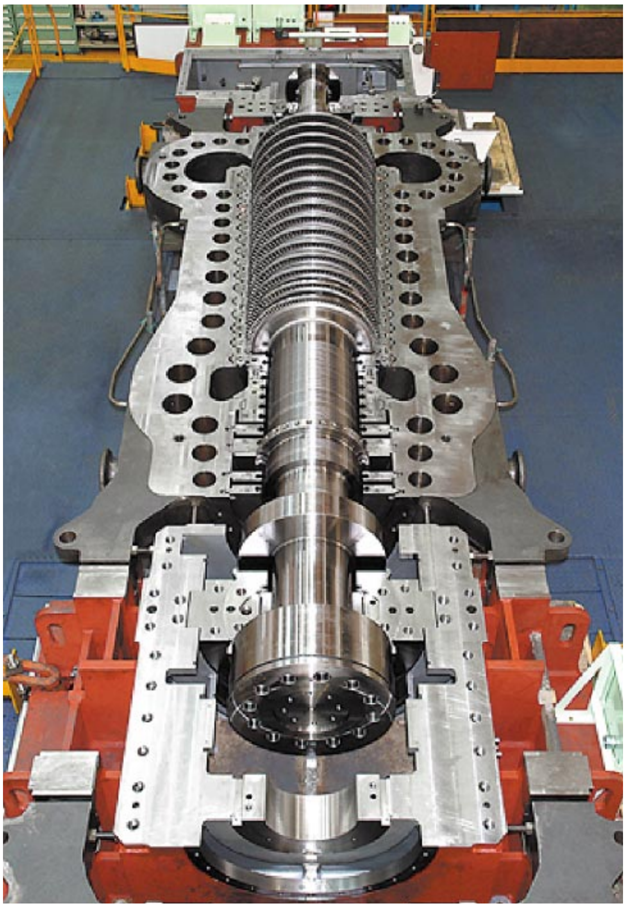

Fig. 8—External View of the High-pressure Turbine Rotor in the Steam Turbine of a Combined-cycle Power Plant.
The high pressure section of the steam turbine for the Kwangyang Combined-cycle Power Plant is composed of 16 turbine stages.

HX blades — is presented in the following.

Kwangyang Combined-cycle Power Plant

The two steam turbines at the Kwangyang Combined-cycle Power Plant of K-Power of Republic of Korea (each with a rated output power of 200 MW) were the first to adopt Hitachi's HX blades, and No. 1 unit started commercial operation in February 2006, and No. 2 unit started the following May.

An overhead view of one of the high-pressure turbines is shown in Fig. 8. This turbine is constructed with the high- and intermediate-pressure sections in a separated casing, and the high-pressure turbine is configured with a total of 16 stages.

As mentioned above, since the high-pressure turbine adopts the HX blades (whose design is optimized in response to flow characteristics), the performance of the turbine in its entirety is improved.

As regards certified performance tests of this high pressure turbine with HX blades performed before delivery to the customer, the certified performance (i.e. turbine efficiency) was satisfactory; that is, it surpassed 0.8%.

CONCLUSIONS

Focusing on the turbines of the Kwangyang Combined-cycle Power Plant of K-Power in Republic of Korea, this report described the newly developed HX blades for these high-pressure turbines.

With an optimum blade profile obtained through a different approach from that for conventional blades, these blades — used particularly for the turbine stages with short blades — significantly improve efficiency compared to the case of conventional blades and, thus, can respond to the efficiency improvements that the market presently demands.

Hitachi, Ltd. will from now onwards strive to widely apply these HX blades in actual turbines in power plants both domestically and internationally.

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