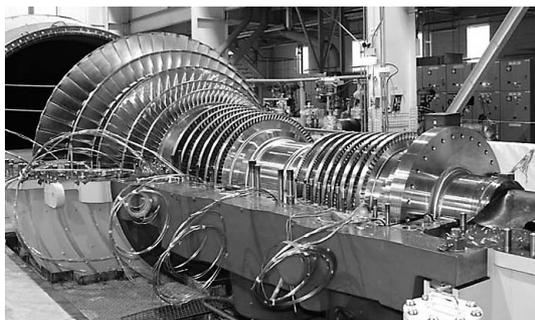


Development of New High Efficiency Steam Turbine



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Mitsubishi Heavy Industries, Ltd. (MHI) has developed new high performance turbine blades (reaction blades, impulse blades, and LP end blades) and high performance seals, as new technologies that remarkably improve the performance of steam turbines. Moreover, MHI has developed a new high efficiency steam turbine, adopting not only these new technologies but also other latest technologies to improve performance and operability. The first unit of new high efficiency steam turbine has started the operation at the “T-point” combined cycle verification power plant in Takasago Machinery Works of MHI, and performance and reliability were verified by special measurements. This article describes the characteristics of the new technologies and the structures that were applied to the newly developed steam turbine and the results of the verification.

1. Introduction

Steady efforts are actively being pursued throughout the world to improve the efficiency of thermal power plants in response to growing movements to conserve energy resources and achieve greater environmental protection typically represented by the control of CO₂ emissions. One of these efforts is an attempt aimed at improving thermal cycles by increasing the steam temperature and pressures handled in the steam turbines. For this purpose, MHI has also realized a high efficiency and large capacity commercial steam turbine that operates at a steam temperature of 600°C class ⁽¹⁾ and has developed materials capable of withstanding temperatures as high as 630°C ⁽²⁾. In addition, MHI has also positively strived to increase the efficiency of steam turbines by improving blade performance, reducing leak losses and so forth. In particular, in order to improve the blade performance, MHI has developed fully three-dimensional design blades to increase their efficiency, applying the latest computational fluid dynamics (CFD) to the maximum extent possible ⁽³⁾, and has adopted such blades for use in actual turbines. On the other hand, in order to cope with growing levels of turbine capacity, MHI has striven to elongate last stage rotating blades, and has led the industry in commercial use of 40 inch steel blades for 3 600 rpm machines and 48 inch steel blades for 3 000 rpm machines ⁽⁴⁾.

In order to improve turbine efficiency, MHI has now developed new high performance reaction blades, impulse blades, and low-pressure (LP) end blades with the intent of achieving further enhancements in efficiency, utilizing the state of the art technologies of three-dimensional multi-stage viscous flow analysis and unsteady flow analysis ⁽⁵⁾. MHI has also developed new high per-

formance seal (Leaf seal) capable of significantly reducing steam leakage through the gland seals and blade tip/base clearance. Moreover, MHI has developed a new high efficiency steam turbine that not only adopts these new technologies but also other latest technologies to achieve high performance and easy operability. The performance and reliability of this new type steam turbine was verified by replacing the existing turbine at the “T-point” combined cycle verification power plant at Takasago Machinery Works of MHI.

2. Outline of new high efficiency steam turbine

The new high performance blades and seals are applicable to all sorts of steam turbines ranging from small sized machines to large scale units for use in combined cycle power plants and conventional thermal power plants. **Fig. 1** shows the first unit of new high efficiency steam turbine that has been developed and manufactured for the T-point verification power plant applying all the new technologies mentioned above.

This turbine is a single-casing reheat type turbine with a rated capacity of 105 MW. The upstream blades of the high-pressure (HP) section are designed for impulse stages, while the downstream blades of the HP section and all the blades of the intermediate-pressure (IP) section are designed for reaction stages. The newly developed high performance blades are applied for both the impulse and reaction stages, with the intent of improving the performance of both stages. The blades of the LP section are composed of 36 inch LP end blades for use in 3 600 rpm operation. These blades are designed by the profile and flow path designs that have been developed based on the latest CFD technology. In addition, leaf seals are applied to the sealing section between the HP exhaust and the gland in order to reduce any steam

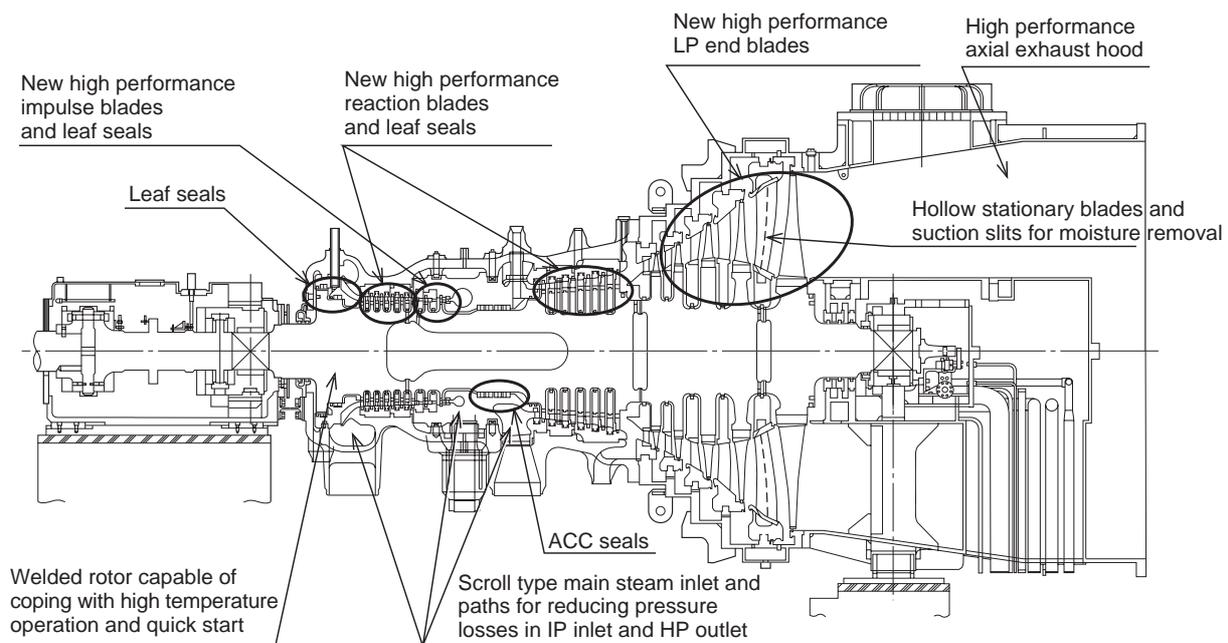


Fig. 1 New high efficiency steam turbine for the T-point (single-casing reheat type turbine)
The notes indicate the position where the new technologies are applied.

leakage. The same type of seals are also applied to the HP and IP rotating blades for sealing the tip clearance in order to improve the blade performance.

In addition to these key technologies, various other technologies have been applied to contribute to improving the performance and operability. For example, the nozzle box for the main steam inlet is designed as a scroll type passage with the aim of homogenizing the steam flow in the circumferential direction and reducing pressure losses, while the shapes of the flow paths at HP exhaust and IP inlet parts have been designed utilizing the CFD so as to reduce pressure losses. The Active Clearance Control or ACC technology applied to the sealing area between the HP and IP sections improves the sealing performance using movable sealing segments. This design results in larger clearance when the turbine is starting or stopping, while a tighter clearance results when the turbine operates under loaded conditions. A welded rotor with large bore structure is employed in order to reduce thermal stresses produced during start-up of the turbine (hetero-material welded rotor)⁽⁶⁾. As a result, the operability of the turbine is improved for quick start.

3. Characteristics of new technologies

3.1 New high performance impulse blades

A newly designed profile that reduces unsteady losses has been applied for the rotating blades of impulse stage adopted as the upstream stages of the HP section of the new high efficiency steam turbine for the T-point. The mechanism of unsteady losses that are produced due to the interaction between the rotating blade and the stationary blade has been clarified through the effective use

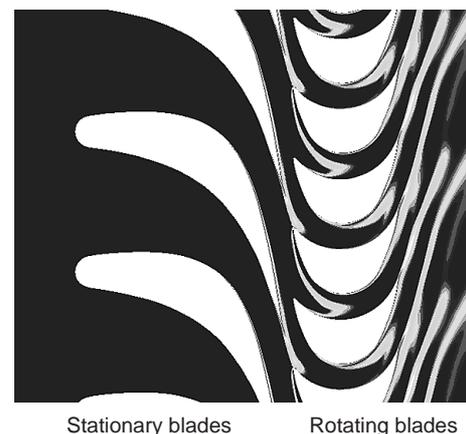


Fig. 2 Example of unsteady flow analysis

of unsteady flow analysis (**Fig. 2**). Based on this knowledge, a new profile was developed to reduce unsteady losses through optimum design. Results of tests at the air turbine facility also confirmed that the performance of the blade was remarkably improved by the new profile.

The structural design of the impulse stages was modified (called high performance diaphragm structure). Conventional wide nozzles are separated into profile sections and support columns. This method is based on the idea that the strength of diaphragm is reinforced by support columns located upstream of the stationary blades and the width of stationary blades can be reduced to increase the aspect ratio. Improvement of stationary blade performance is also achieved by applying a three-dimensional design. The shape of the support columns and the profile of stationary blades are optimized through the use of three-dimensional flow analysis.

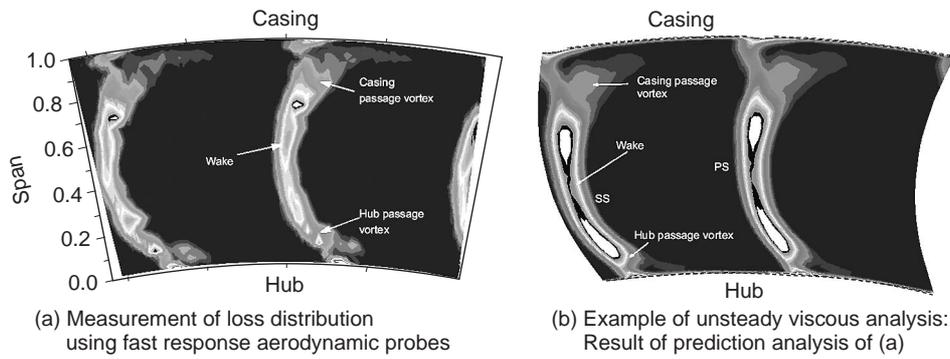


Fig. 3 Example of improvement of prediction accuracy using flow analysis

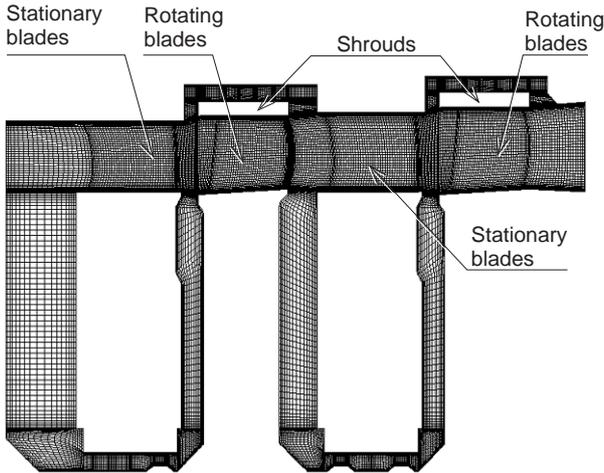


Fig. 4 Example of computational mesh grids for analyzing entire stream path (Downstream of HP section)

3.2 New high performance reaction blades

MHI has always made steady efforts to improve the accuracy of the predictions of efficiency and internal turbine flows. Three-dimensional multi-stage flow analysis taking viscosity into consideration was used for this purpose and the results of this analysis were confirmed at air turbine verification test. Recently, in addition to conventional steady state analysis, MHI has established an unsteady flow analysis method capable of predicting loss-producing mechanisms even more precisely, as shown in **Fig. 3**. As a result, MHI has developed new high performance reaction blades using these methods.

The degree of reaction and the three-dimensional stacking of profile are further optimized, compared with the flow patterns of conventional blades. As a result, production of the secondary flow vortices are controlled and the vortex zones are shifted toward the inside and outside endwall of each blade, so that losses due to the secondary flows in the rotating blades are reduced. In addition, a new profile to reduce unsteady losses produced by the interaction between the rotating blades and stationary blades is applied to the middle zone of the blade height where profile losses are dominant.

Unsteady flow analysis has also quantitatively clarified that vortices produced in the vicinities of the inside and outside endwall of each blade due to leakage from and inflow into the spaces between each rotating blade

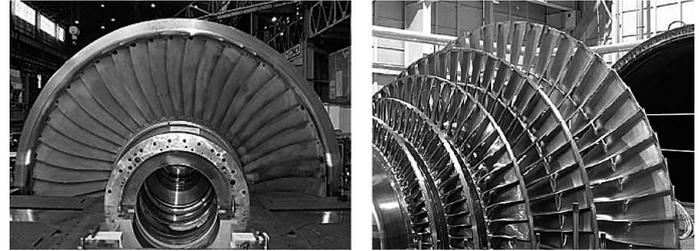


Fig. 5 New high performance LP end blades (3600 rpm - 36 inches)

and stationary blade interact with secondary flow vortices and increase the secondary flow losses. Accordingly, MHI has attempted to optimize the shape of the flow paths including those between the inside circumferences of the stationary blades and the rotor disks and those around the rotating blade shrouds. **Fig. 4** shows an analysis model of the flow fields including all of these flow paths.

As described above, new high performance reaction blades have been developed through the latest analysis technologies and the detailed verification of the internal flows, and applied to the downstream blades of the HP section and to all the blades of the IP section of the new type steam turbine at the T-point.

3.3 New high performance LP end blades

The performance of the LP end blades largely influences the performance of the turbine as a whole. Consequently, MHI has striven to realize its various improvements taking the progress of the flow analysis technologies. The 3600 rpm 36 inch blades shown in **Fig. 5**, which have been developed this time as new high performance LP end blades based on the latest unsteady multi-stage viscous flow analysis, demonstrate further advanced performance. This latest unsteady flow analysis can be used for evaluating the behavior of the wakes of stationary blades inside the downstream rotating blades in multi-stage flow field, the behavior of wakes of rotating blades inside the downstream stationary blades, the interaction between wakes and secondary flows, and the interaction between shock waves and boundary layers or secondary flows. The improvement in the performance has been realized by taking these effects into consideration, in addition to the optimization of

stage loading, loading distribution along the blade height and the blade profile for high Mach number flow, which have been implemented so far. Since these effects in unsteady flow field are evaluated at every moment, the design was made to achieve maximum efficiency by time-averaging.

The advance of the flow analysis technology has remarkably increased the prediction accuracy of exciting forces acting on a blade and enabled to improve vibratory strength of the blades largely. This increases the degrees of freedom related to the flow path design and stacking of the blade profiles, enabling MHI to thoroughly review the design to improve performance. As a result, the base diameters and heights of the upstream rotating blades as well as the lengths of the last stage blade could be increased, and the flow fields of the LP end blades as a whole including the blade endwall contours has been further optimized. Further, the skewed profile inclined in the axial direction, in addition to the conventional bowed profile, was adopted for the stacking of the stationary blades.

On the other hand, it has also become possible to predict drain trajectories precisely using the flow analysis described above, so that the positioning of the drain slits can be optimized in order to reduce losses caused by drain (moisture losses) peculiar to the LP end blades.

3.4 Seal technology

In developing a new high efficiency steam turbine, MHI has striven to develop and apply new sealing and clearance-controlling technologies that contribute to improving turbine performance, as well as the technologies to improve the performance of blades. The new sealing technologies also make it possible to reduce the axial span needed to seal each section of a turbine, compared with conventional labyrinth seals, by improving sealing performance. This also allows the design of the shaft system and blades to have some margin.

3.4.1 Leaf seals

The structure of leaf seal is shown in **Fig. 6**, and the mechanism of its operation is shown in **Fig. 7**. The leaf seal is a seal based on a new design concept that differs from non-contact type seals represented by conventional labyrinth seals and from contact type seals such as brush

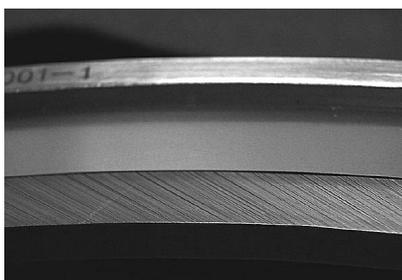


Fig. 6 Structure of leaf seal

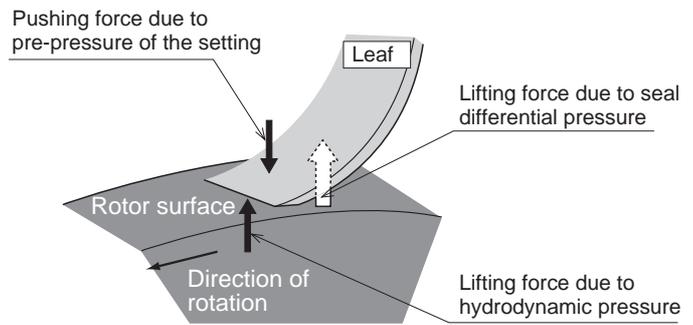


Fig. 7 Mechanism of leaf seal operation

The tip of the leaf is lifted-up by a balance of the pushing force due to pre-pressure of the setting, lifting force due to hydrodynamic pressure generated during rotation of the rotor, and lifting force due to the differential pressure of the seal.

seals whose application has been expanding recently. This seal consists of a number of thin metal plate (leaf) inclined in the circumferential direction so that the tip of the seal is kept in a non-contact state with negligibly small clearance when the rotor is rotating. This is done by a lifting force produced due to a hydrodynamic pressure effect acting between the tip of the leaf and the rotor. The result is that both the seal and rotor are prevented from wear and the durability of the seal is increased when the turbine is running, different from contact type seals such as brush seals. In addition, since the seal itself is in the shape of plate with axial width, it has a higher rigidity in the direction of the pressure difference and the sealing function can be kept up to a higher differential pressure compared with brush seals.

Fig. 8 shows the results of the verification test of seal performance and lifting characteristics (test to verify the electricity discontinuity between the seal and rotor) carried out in the shop. The results confirm that the flow rate through the seal can be reduced to about one-third that of conventional labyrinth seals. The result of the electricity discontinuity test also indicates that the lifting-up of the seal is performed well even if the seal is eccentrically positioned against the rotor. The leaf seal has already installed and tested at the existing steam turbine of the T-point power plant and soundness was confirmed during inspections carried out one year after the verification operation was begun. The further improved seals are applied to the new type steam turbine for the T-point.

3.4.2 ACC (Active Clearance Control)

The structure of the ACC is shown in **Fig. 9**. The ACC seal is a seal with a structure in which segments of labyrinth seal rings are made to be movable in the radial direction. When the turbine is starting, stopping or during turning operation after stopping, the segments are raised by a spring force to keep the clearance between the rotor and the seal fins large. On the other hand, when the turbine load is increasing, the seal segments are shifted until the proper clearance is maintained radially toward the center by utilizing the pressure

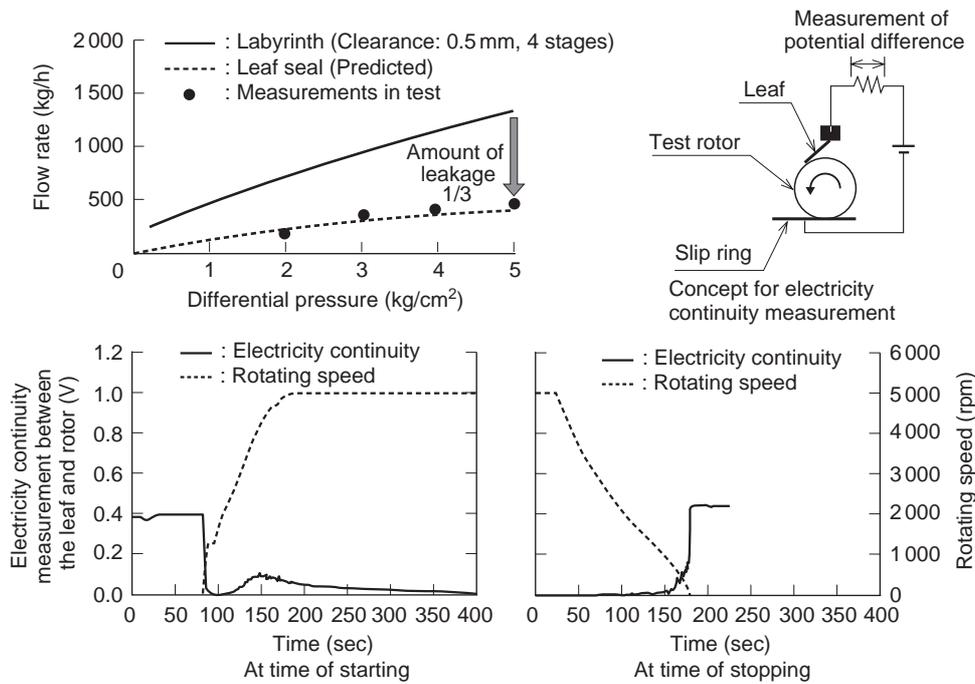


Fig. 8 Results of verification tests of leaf seal performance and lifting characteristics of the leaf

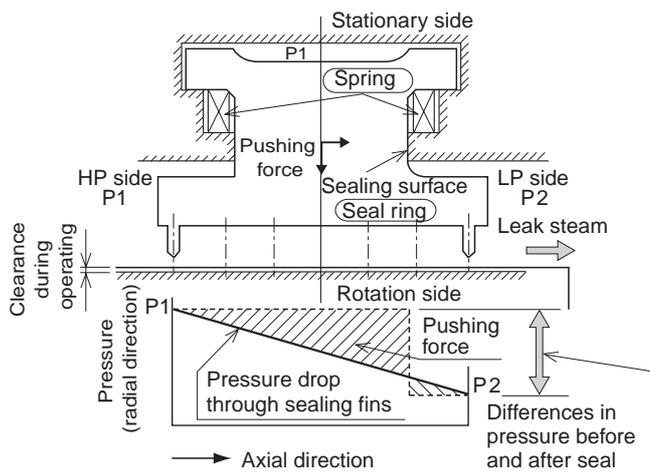


Fig. 9 Construction of ACC
Seal ring moves in the radial direction as a result of the difference in force between the spring force and the force due to the differences in pressure between the inner and outer circumference of each seal ring.

difference for sealing. Then, the narrowest clearance is kept during the loaded operation.

The verification test of the ACC seal in the actual machine has already been carried out at the existing steam turbine of the T-point power plant. The movement of the ACC seal segments was measured using gap sensors. As a result, it was confirmed that the clearance enlarged and narrowed together with the start and stop of the turbine, thereby ensuring that clearance control is performed precisely. Inspections carried out one year after the operation of the turbine confirmed that the seal fins on the ACC seal segments remained sound, while traces of wear were found in the seal fins of the conventional segments installed adjacent to the ACC

seal. Based on these results, these seals have been adopted to nine turbines including a 700 MW unit and have started actual operations.

In the new type steam turbine developed for the T-point, four stages of the ACC seal are installed in the line at the HP dummy ring. In this case, wear of the seal fins due to deformation of the casing during starting and stopping of the turbine is avoided by controlling the pressure distribution and spring force of each segment. During the rated load operation, the clearance is kept small in order to reduce any leak losses and to improve the performance of the turbine.

4. Verification tests on the actual turbine

The new high efficiency steam turbine provided with various new advanced technologies and installed at the T-point verification power plant replacing the existing turbine began operations in May 2003. In this turbine, pressure and temperature sensors have been installed at the necessary points inside the turbine casing in order to confirm the improvement in the performance of each component, that achieved through the application of new technologies, as well as the improvement in the performance of the turbine as a whole. The measurement of the internal flows in the IP blades, LP blades, and the exhaust hood is also carried out using Pitot-traversing devices. In addition, confirmation of the performance of the seals was carried out by measuring the differential pressure through each seal and the gap between the rotating parts and stationary parts (Fig. 10).

The test results show that improvements in the performance of entire turbine were as expected. The results also confirmed that the performances of the new high

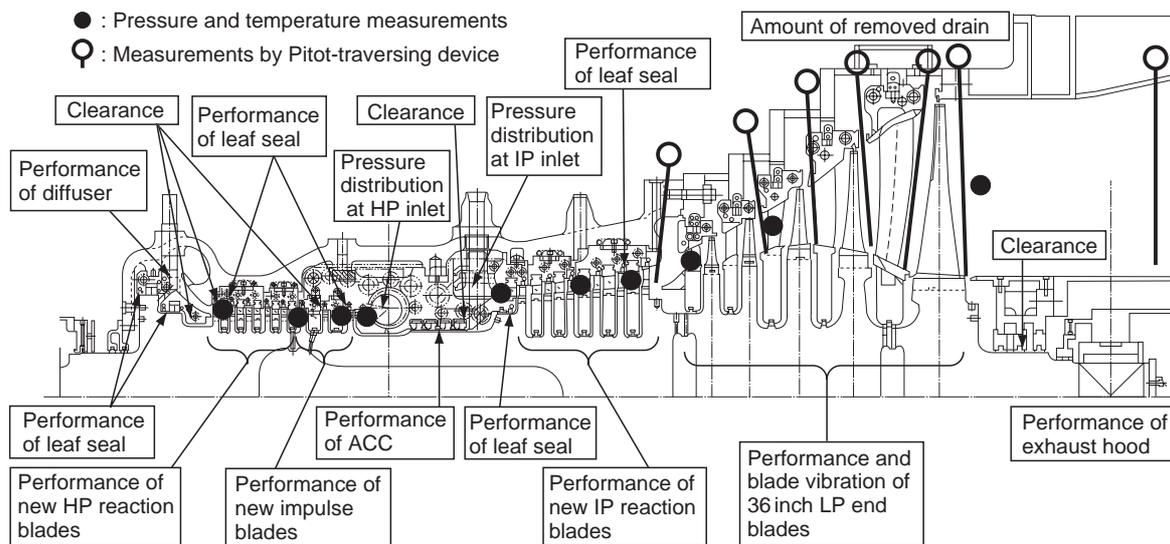


Fig. 10 Special measurement points in the new steam turbine for the T-point

performance blades applied to the HP section, the IP section and the LP end blades as well as the advanced components such as the leaf seals, ACC seals, and passage for reducing inlet and outlet losses were achieved as planned.

5. Conclusion

MHI has successfully developed a new high efficiency steam turbine by integrating a range of techniques to realize the latest advanced technologies. Results of verification tests carried out with the new steam turbine for the T-point power plant confirmed that improvements in performance could be achieved as intended, and verified the reliability of the turbine and its each component. The new technologies adopted in this new type steam turbine can contribute to the improvement of the efficiencies of a wide range of turbines from small and medium sized turbines to large scale turbines. Hence, it is planned that these technologies will be successively applied to both newly installed turbines and existing units.

MHI will continue to develop advanced technologies aimed at achieving ever higher levels of efficiency in power plants and higher performance in steam turbines through the application of these technologies.

References

- (1) Tanaka et al., Feature and Operating Experience of 1000 MW Class Steam Turbine with Highest Efficiency in the World, Mitsubishi Juko Giho Vol.39 No.3 (2002) p.132
- (2) Yoshikuni KADOYA et al., "Alloy Design and Production of an Advanced 12Cr Steel Rotor Applicable to Elevated Steam Temperatures", Fifth International Conference on CLEAN STEEL (1997)
- (3) Sugitani et al., Development of Advanced High Performance Blades and Their Operating Experience, Mitsubishi Heavy Industries Technical Review Vol.31 No.3 (1994) p.125
- (4) Hiroharu OHYAMA et al., Development of High Efficiency and Reliability Low Pressure End Blade, The 8th National

Symposium on Power and Energy Systems (SPES 2002), Tokyo, (2002.6), p.141

- (5) V.S.P.Chaluvadi et al., Blade Row Interaction in a High Pressure Steam Turbine, Transaction of the ASME, Journal of Turbomachinery Vol.125 No.1 (2003) p.14
- (6) Shige et al., Development of Large-Capacity Highly Efficient Welded Rotor for Steam Turbines, Mitsubishi Heavy Industries Technical Review Vol.38 No.1 (2001) p.6

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