Analysis and Evaluation of Applicability and Modification Effect of New Style Steam Seal for Steam Turbine

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Abstract. According to structural feature and operating characteristic of several kinds of new style steam seal, their application position in flow passage and axle head is introduced in this paper. Energy saving effect is generalized by synthetically analyzing several parameters, which are tested before and after the seal modification with the same testing point and condition, including heat consumption rate, cylinder efficiency, monitoring parameters, steam seal leakage. The steam seal modification of 660MW unit shows remarkable improvement with HP cylinder efficiency increasing from 2.7% to 3.1%, IP cylinder efficiency increasing from 1.6% to 1.7%, heat consumption rate decreasing by 210kJ/kW.h. The leakage from steam seal between HP and IP cylinder to LP cylinder accounts for 1.283% of main steam flow，which decreases to 0.8945% after the steam seal is modified，as well practical IP cylinder efficiency increases from 89.544% to 91.27%. In addition to the above improvement, the leakage from HP rear shaft seal to IP exhaust, temperature rise of condensation water through gland steam condenser, pressure of shaft seal and monitoring parameters also decrease apparently.

Introduction

Modern steam turbine mostly adopts the steam seal of comb type structure. In recent years, with the development of technology, a variety of new types of steam seal are introduced from abroad, which are typically honeycomb seal, brush seal, adjustable seal, contact seal, lateral teeth gland, and so on. Although the structures of these steam seal are different, but the designer's guiding idea is to improve the sealing effect and reduce the leakage loss by adding the teeth number, reducing the gap and increasing resistance [1, 2]. At present, all kinds of new type steam seal are widely adopted in energy-saving modification of the steam turbine, but different steam seal has different technical and working characteristics, different applicable scope, and energy saving effects also differ greatly in different modification plans. Based on the working characteristic of steam seal, this paper analyzes the applicable scope of various steam seal and the energy saving effect of a 660MW unit of steam seal modification.

The Necessity of Modification with New Style Steam Seal

The disadvantage of traditional comb tooth seal. At present, comb tooth seal is mostly used as steam seal for steam turbine. The sealing principle of comb tooth seal is to reduce the steam leakage by the repeated throttling expansion processes which steam pass through annular apertures between seal tooth and rotor, and annular chambers between adjacent teeth and rotor. Thus, the space size of annular apertures and annular chambers is the critical factor to influence sealing effect.

The disadvantages of comb tooth seal are as follows.(1) The chambers between seal teeth are annular, and could cause steam annular flowing which weakens the slowdown effect of eddy current, therefore, the barrier effect of comb tooth seal is poor and steam leakage is larger.(2) If the steam clearance is non-uniform, the fluid vibration will be formed, which will break the operation stability of the rotor.(3) Because the expansion difference is bigger during start-up or shut-off, the low teeth of steam seal are easy to drop off and the high teeth are easy to fall over, which would increase the steam leakage and also increase expansion difference, finally to endanger the operating security of the unit.(4) Steam leakage is proportional to size of the seal clearance. Therefore, both of seal clearance and steam leakage increase remarkably as seal tooth is worn.

For traditional units, the seal clearance is designed as big as possible because of the limitation of comb type seal. If we reduce the seal clearance, it will cause the unit steam flow vibration and friction, especially when the unit go through the critical speed, it often brings about wear of labyrinth strips and even cause rotor thermal bending deformation, and brings to great potential safety hazard.

Necessity of modification with new style steam seal. There are many factors influencing turbine efficiency, mainly including leakage of moving blade top seal, leakage between diaphragm seal and shaft, rough and corrosion of moving blade, rough and corrosion of nozzle, deposit and other loss caused by unit maintenance, which respectively accounts for about 35%, 9%, 10%, 18%, 14% and 14% of the total loss, of which the seal leakage could sum to 44% of the turbine total loss[3,4].

For traditional comb tooth seal, during unit startup, uneven thermal deformation of cylinder body, diaphragm seal and gland casing will reduce radial clearance between part of seal teeth and rotor, leading to the collision and wear of the steam seal, which could be irreversible damage when the rotation rate increases to critical speed. The steam leakage can be decreased through unit overhaul, however, it changes back to the same level as before after the operation of a period of time. So, during design and maintenance of steam turbine, adopting new type steam sealing and adjusting the reasonable seal clearance is an important way for safety and economy of unit operation. However, different kind of steam seal has different scope of application, normally many kinds of steam sealing are adopted for modification scheme of steam sealing of steam turbine.

Structure and Applicable Position of New Style Steam Seal

Structure and applicable position of honeycomb seal. The inner face of the honeycomb seal ring is a honeycomb belt regularly ranged by lots of regular hexagonal honeycomb holes, which are welded with high temperature alloy plate of 0.05mm~0.20mm by special welding equipment. The honeycomb seal can increase damping effect by steam turbulence produced when the leakage flows through honeycomb belt, and at the same time, the special structure of the honeycomb also produces adsorption effect, as well as friction sealing function, which can achieve good sealing effect. For low pressure cylinder, the honeycomb seal can be arranged on top of last stage and the penultimate stage blades, which can prevent moving blade from water erosion because of the honeycomb seal characteristics of big surface area and water adsorption. So, it is widely used as shaft seal and steam seal in flow passage of LP cylinder of steam turbine.

Structure and applicable position of brush seal. The seal ring of brush seal is composed of numerous cobalt-based alloy wires with 0.05～0.15mm diameter. The cobalt based alloy wires are arranged into brush row with the same radian with seal blocks by a dedicated wire arraying machine, which can bear at a speed of more than 305m/s and the temperature of up to1200℃. The assembled clearance is generally controlled to be 0.05～0.25mm,and the brush wire is elastic to give up clearance of up to 2mm,not easy to be wear off. So, it can ensure the unit safe operation in the lower limit of design seal clearance. Brush seal can be applied in all positions of HP, IP and LP cylinders, and widely used at present.

Structure and applicable position of touching seal. Touching seal is the sealing ring of special material directly embedded in the labyrinth base of traditional comb tooth seal, which can touch the rotor directly. The sealing teeth of touching seal are usually made of multi-composite material with the characteristic of wear-resisting, oil resistance, high temperature resistance, as well as self lubricating function, The sealing ring can always keep approximately touch with the rotor by pre-tightening force producing by the spring on its back, and can back down automatically by the elastic force of spring.

Touching seal is usually used on outer end of shaft seal in order to reduce steam leakage. When seal pressure is high, the touching seal can prevent vapor from getting into lubrication oil tank which would cause oil e emulsifying, and when seal pressure is low, the touching seal can prevent air from leak inside in order to improve the vacuum of the unit.

Structure and applicable position of soft tooth seal. Soft tooth seal is composed of several layers of heat-resistant and anti-corrosion special-metal cloth arranged into U-shape steel jackets, which changes the rigid structure, makes the seal teeth to be elastic. And the radial clearance between seal tooth and rotor is usually designed as 0.2-0.4mm. As the soft tooth is elastic, when collision happens between stator and rotor during unit startup and shutoff, seal tooth falls down to steam-admission side. However, the collision above is elastic touching because the soft teeth are elastic and can't damage the seal teeth and rotor. When the collision stops, soft teeth, as well as labyrinth clearance can return to the original position for the reason of elasticity and steam force. As the reasons above, the soft tooth seal is usually used in shaft end.

Structure and applicable position of Bladen seal. Instead of using blade spring in back of the traditional seal ring, Bladen seal uses four coil springs on cross section of each seal ring. When the unit is out of service, the seal arc blocks are pushed away by the spring in order to keep a relatively big distance from rotor. When the unit is starting up, with the steam flow increasing, the steam pressure force on back of seal arc blocks increases fast until the seal block shut downs to a balanced state and operates with the smallest radial clearance from rotor. However, when the unit shuts off, with the steam flow decreasing, the steam pressure force on back of seal blocks decreases fast and the seal blocks are pushed away by the spring in order to keep a relatively big distance from rotor.

The advantages of Bladen seal is that it can keep suitable radial clearance during startup or shutoff, so it is usually used in diaphragm seals of HP and IP cylinder, on which the pressure difference before and after stages can meet its requirements. Bladen seal is not suitable for LP stages and shaft seal where the pressure difference is small. It is also not suitable to be used as blade top seal, as the loss caused by steam leakage through the prepared clearance between two blocks is larger than the benefit brought by adjusting radial clearance.

Structure and applicable position of side tooth seal. Side-tooth seal is developed on the basis of comb tooth seal. Without changing the original structure, the teeth is machined with side and bottom teeth, equal to dividing the single chamber into several small ones. So for the same length seal section, the steam flow passage in side-tooth seal is more complex and has more seal teeth, thus presenting better performance in reducing steam leakage. Side tooth seal is usually used for shaft end seal and diaphragm seal to enhance the effect in reducing steam leakage.

Structure and applicable position of DAS seal. DAS seal is also called as the big tooth seal, with the similar structure with traditional comb tooth seal. But DAS seal teeth are wider, which have better and more stable throttling effect. The big tooth of DAS seal has better wear-resisting performance compared with traditional comb tooth seal especially when collision between seal and rotor happens. With the protection of DAS teeth, the other teeth of steam seals can keep the designed clearance to rotor to reduce steam leakage effectively in an overhaul period.

As it can bear high pressure difference, DAS can be widely used for any position, such as diaphragm seal, gas bridge seal (the seal between HP and IP cylinder), or balancing drum, which can bear relatively pressure difference. In HP and IP cylinder, DAS seal can keep the uniform stability of the seal clearance and restrain gas exciting effectively for its uniformity and stability of labyrinth clearance.

New styles of steam seals in different positions of steam turbine. If the steam seals of steam turbine are modified or changed, the scheme can be made comprehensively according to operating history and safety index of the unit, which mainly includes vibration, differential expansion, temperature difference between the upper and the lower casing of the cylinder, etc. The new style steam seals in different positions of steam turbine are showed in Table 1.

Table 1. New Style Steam Seals in Different Positions of steam turbine

Positions of steam turbine	Style of Steam Seal
Balance drum between HP and IP	Bladen seal, honeycomb seal
Diaphragm of HP cylinder	Bladen seal, honeycomb seal
Blade top of HP cylinder	Honeycomb seal
Diaphragm of IP cylinder	Bladen seal, honeycomb seal, brush seal
Blade top of IP cylinder	Honeycomb seal
Diaphragm and blade top of LP cylinder	Honeycomb seal, brush seal
Shaft seal of HP，IP and LP cylinder	Bladen seal, honeycomb seal, touchable seal，Bladen seal （inside of rear shaft seal of HP cylinder）
Shaft end seal of HP，IP and LP cylinder	Soft tooth seal and touch able seal can be used for shaft end seal of LP cylinder
Shaft seal of steam turbine for pump	Brush seal，touchable seal

Appropriate steam seals shall be chosen according to the specific position, if the steam seal or shaft seal is modified for steam turbine. A good modification scheme is to combine several kinds of steam seals.

Evaluation Analysis of Modification Effect

In order to determine whether it is necessary to make seal modification or replacement, we can evaluate the energy saving effect of the seal reconstruction from the following several aspects, according to the turbine structure and thermal properties.

Temperature of monitoring section. It is a common way using the relative changes in extraction steam temperature of each stage to evaluate the effect of modification, especially for the turbine with two steam extractions in a HP cylinder which there are usually two types of structures. For one type, NO.1 extraction steam is designed on outer casing of HP cylinder with front and rear interlayer. So when the steam leakage of balancing drum seal gets into the cylinder interlayer largely, the temperature of NO.1 extraction steam would certainly be higher. For another type, NO.1 extraction steam is designed on inner casing of HP cylinder. If the steam leakage of balancing drum seal of inner casing is large, HP cylinder exhaust temperature of the last stage blade outlet is 2-3 ℃ less than exhaust steam pipe. For the two types of HP cylinders, the NO.1 extraction steam or high exhaust temperature change before and after modification can be as the basis of evaluating the seal modification effect.

Steam leakage of balancing drum between HP and IP cylinder. For steam turbine with combined

HP-IP casing, the steam leakage of balancing drum between HP and IP cylinder can be tested by the steam temperature variation method (STVM). It can be used to evaluate the energy-saving effect to analyze the relative change of steam leakage of balancing drum before and after steam seal modification.

Self-sealing pressure of shaft seal. Self-sealing system is widely used for shaft seal of steam turbine unit. The gland seal load for self sealing before and after the modification would change with three ways.(1)Modification is only made for LP cylinder shaft seal. For this case, the pressure of main sealing pipe can maintain at a low level, so the self-sealing load decreases after modification.(2)Modification is only made for HP and IP cylinder shaft seal. For this case, the self-sealing load increases after modification.(3)Modification is made for HP, IP and LP cylinder shaft seal at the same time. For this case, the effect of modification for LP shaft seal can be judged by adjusting the main sealing pipe pressure to a low level that can still maintain the unit vacuum. Then, it is also need to observe the relative change on the no overflow and no external steam supply load point than that before modification.

Temperature rise of gland steam condenser(GSC). The temperature rise of gland steam condenser(GSC) is usually designed as about 1℃, however it is higher obviously in actual operation than design value. The effect of shaft seal modification can be analyzed by comparing the relative change of temperature rise of GSC with the steam leaking into GSC.

Declining of internal efficiency of IP. The nominal efficiency is the internal efficiency of IP cylinder calculated with the measured parameters before main throttle valve of IP cylinder and those of exhaust steam. For steam turbine of combined HP-IP casing, nominal efficiency of IP cylinder is usually 2% higher than practical efficiency because balance drum leaks. So, if the steam seal modification is successful, the internal efficiency will decline. Otherwise, this modification can't work well.

Seal Modification Scheme and Energy Saving Effect Analysis

Evaluating the efficacy of the seal modification should base on the structural characteristics of steam turbine, the specific position of seal modification, and choose the same measurement point and test conditions before and after modification to carry out the unit performance tests. Through the above several methods or a combination of several measured parameters, the integrated analysis is made to evaluate whether seal modification achieves the desired effect.

Seal modification scheme of supercritical 670MW unit. One 660MW unit modified is a supercritical, single shaft, three cylinder (combined HP-IP casing), four-exhaust steam, one reheat and condensing turbine. During overhaul, Steam sealing is modified on the following aspects.(1) The comb tooth of front and rear shaft seal is replaced with honeycomb seal in the HP and IP cylinder .(2) The LP shaft seal is modified to be comb and touching tooth seals, of which the outer two rings and inner one ring are touching tooth seal.(3) For LP cylinder, the comb tooth seals of the one to four stage top blade seal of both positive and negative are replaced with honeycomb seal.(4)The excessively attrited seal of HP nozzle is replaced with new one.

Energy saving effect analysis after seal modification. For the modification scheme of supercritical 660MW above, the overhaul and seal modification effect is evaluated by the parameters of heat consumption rate, HP and IP cylinder efficiency, gland seal leakage quantity, gland steam condenser parameter change and monitoring section parameter change of steam turbine. The result shows that the improvement of HP and IP cylinder efficiency, heat consumption rate and parameters of monitoring section covers the effect of both overhaul and seal modification, while seal leakage quantity and GSC parameter change is mainly effected by modification and adjustment of shaft seal and steam seal.

Heat consumption rate and cylinder efficiency. The tests before and after modification and overhaul adopts the same flow base in order to calculate economy parameters. Table 2 shows the heat consumption rate and cylinder efficiency of the tests.

Table 2. Performance test results of supercritical 660MW unit before and after seal modification

		After seal modification		Before seal modification	
Parameter	Unit	THA condition	600MW condition	THA condition	600MW condition
Generator output power	kW	668256.8	601601.9	658592	599428
Generator power after the second class correction	kW	694555.8	623482.3	667909.3	602028.7
Efficiency of HP cylinder	%	85.048	83.259	82.290	80.194
Efficiency of IP cylinder	%	91.724	91.846	90.151	90.163
Heat consumption rate	kJ/kW.h	7913.497	7999.615	7975.13	7929.299
Heat consumption rate after the second class correction	kJ/kW.h	7642.052	7740.622	7910.408	8000.64

The result in Table 2 shows that the efficiency of HP and IP cylinder increases respectively by 2.7-3.1% and 1.6-1.7% after overhaul and seal modification, and the heat consumption rate decrease by about 210 kJ/kW.h.

Steam leakage of balance drum seal between HP and IP cylinder. STVM tests are carried out on the three valve point condition, on which the steam leakage of balance drum seal and practical IP cylinder efficiency are calculated as showed in Table 3.

Table 3. STVM test result of supercritical 660MW unit before and after seal modification

Parameter	Unit	Before seal modification		After seal modification	
		STVM1	STVM2	STVM1	STVM2
Generator output power	MW	640.714	638.613	641219.1	639252.6
Main steam temperature	℃	531.731	561.443	562.358	530.861
Main steam pressure	MPa	24.1295	23.9553	24.1261	24.2268
Main steam flow	kg/h	1986802.8	1921338.9	1936213.4	1993948.7
Pressure after adjusting stage	MPa	18.0393	17.9379	18.0702	18.1485
Temperature after adjusting stage	℃	489.817	519.83	519.088	487.01
Efficiency of adjusting stage	%	59.390	59.374	64.607	67.524
Reheat steam temperature	℃	547.472	536.818	530.468	544.255
Reheat steam pressure	MPa	4.1519	4.1208	4.1303	4.163
IP exhaust temperature	℃	358.633	350.535	344.084	354.818
IP exhaust pressure	MPa	1.1327	1.1243	1.1424	1.1508
Nominal IP cylinder efficiency	%	90.428	90.089	91.631	91.891
Steam leakage of balance drum seal（accounting for main steam flow）	%	1.283	1.283	0.8945	0.8945
Actual IP cylinder efficiency	%	89.544	89.544	91.27	91.27

As Table 3 shows, the steam leakage of balance drum seal is 1.283% accounting for main steam flow before modification, while it is 0.8945% and decreases by 0.389% after modification. After the modification, actual IP cylinder efficiency increases by 1.726%, while nominal IP cylinder efficiency increases by 1.6-1.7%.The increase of actual efficiency is higher than that of nominal efficiency, which also shows that before modification, the higher nominal efficiency of IP cylinder is due to the effect of steam leakage. Figure 1 and Figure 2 show the relationship between IP cylinder efficiency and steam leakage rate of balance drum seal between HP and LP cylinder.

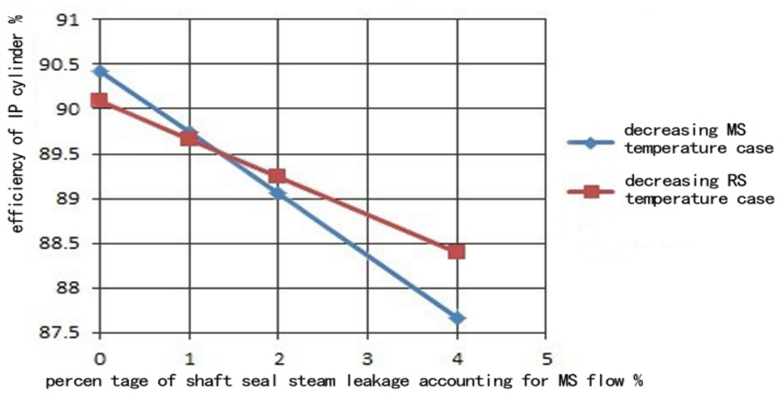

Figure 1. Relationship between IP cylinder efficiency and steam leakage rate of balance drum seal between HP and LP cylinder before modification

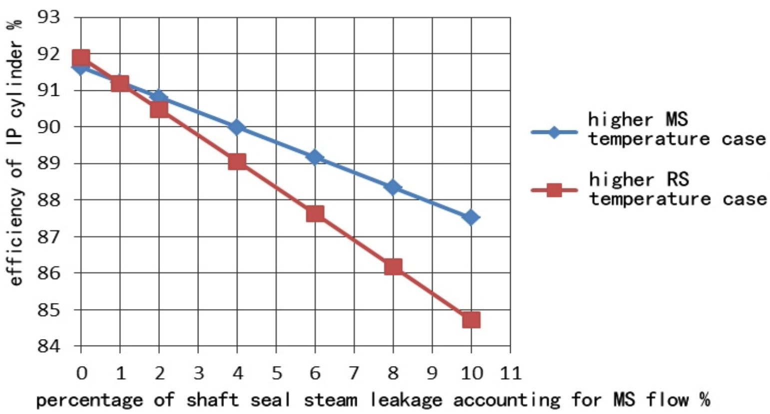

Figure 2. Relationship between IP cylinder efficiency and steam leakage rate of balance drum seal between HP and LP cylinder after modification

Steam leakage of shaft seal and parameters of GSC. Before and after overhaul and steam seal, some parameters are actually measured, such as the leakage from first rear shaft of HP cylinder to IP exhaust, inlet steam parameters of GSC, inlet and outlet water temperature of GSC and so on. Table 4 shows the result of test.

Table 4. Test result for seal steam leakage of supercritical 660MW unit before and after seal modification

Parameter	unit	Before modification		After modification	
		STVM1	STVM2	STVM1	STVM2
Generator output power	MW	640.714	638.613	641219.1	639252.6
Leakage from first rear shaft of HP cylinder to IP exhaust	kg/h	19427.4	19427.4	18337.8	18853.4
Inlet water temperature of GSC	℃	35.13	35.465	43.792	44.344
Outlet water temperature of GSC	℃	37.67	37.885	45.542	46.167
Temperature rise of GSC	℃	2.54	2.42	1.75	1.823
Pressure of shaft seal	kPa	0.1414	0.1412	0.1086	0.1084

The result above shows that, after modification leakage from first of rear shaft of HP cylinder to

IP exhaust, temperature rise of GSC and pressure of shaft seal all decrease, proving the good seal modification effect.

Parameter compare of monitoring section. After overhaul and seal modification of supercritical 660MW unit, on the condition that the main steam temperature and reheat steam temperature is similar, the exhaust temperatures of HP and IP cylinders are obviously decreased, as well as the temperatures of NO.1, NO.3, NO.5, and NO.6 stage extracting steam, as shown in Table 5. All of these prove that unit overhaul and gland after modification, the inter-stage steam leakage quantity of inner flow passage decreased significantly after overhaul and seal modification.

Table 5. Parameters compare of monitoring section for supercritical 660MW unit before and after seal modification

Parameter	unit	THA condition before modification	THA condition after modification
Generator output power	kW	658592	668256.8
Main steam flow	kg/h	1973283.4	2013825.1
Main steam pressure	MPa	23.9946	24.1437
Main steam temperature	℃	563.262	563.045
NO.1 stage extraction steam temperature	℃	377.19	370.110
HP exhaust temperature	℃	324.787	321.17
Reheat steam temperature	℃	560.43	557.111
NO.3 stage extraction steam temperature	℃	478.587	465.039
IP exhaust temperature	℃	370.003	365.889
NO.5 stage extraction steam temperature	℃	277.213	268.485
NO.6 stage extraction steam temperature	℃	193.981	188.817

Conclusion

According to structural feature and operating characteristic of several kinds of new style steam seal, their application position in flow passage and axle head is introduced in this paper. So the suitable seal type shall be chosen according to the modification position of steam seal and shaft seal.

For the seal modification scheme of one concrete turbine, some parameter’s change can evaluate the effect of overhaul and seal modification, including heat consumption rate, efficiency of HP and IP cylinder, leakage of steam seal, pressure of gland seal, GSC parameter, monitoring section parameter, and so on. The improvement of HP and IP cylinder efficiency, heat consumption rate and monitoring section parameters are effected both by overhaul and seal modification, while seal leakage, GSC parameter and shaft seal pressure are mainly effected by seal modification and adjustment. Energy saving effect is evaluated by synthetically analyzing several parameters including heat consumption rate, cylinder efficiency, monitoring parameters, steam seal leakage and so on, which are tested before and after the seal modification with the same testing point and condition.

In view of the concrete seal modification of supercritical 660MW steam turbine, the result of steam turbine thermal performance test before and after modification can analyze the energy saving effect of the overhaul and seal modification as showed below. HP cylinder efficiency increase from 2.7% to 3.1%, IP cylinder efficiency increases from 1.6% to 1.7%, and heat consumption rate decreases by 210kJ/kW.h. The leakage from balance drum seal between HP and IP cylinder accounts for 1.283% of main steam flow, which decreases to 0.8945% after the steam seal is modified， while actual IP cylinder efficiency increases from 89.544% to 91.27% with the improvement of 1.726%. In addition to the above improvement, the leakage from first rear shaft seal of HP to IP exhaust, condensation water temperature rise through GSC, pressure of shaft seal and monitoring parameters also decrease apparently. All of these state the good energy saving effect of seal modification of steam turbine.

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