Research on Method of the Flow Passage Condition Monitoring and Diagnosis for Steam Turbine

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Abstract. Monitoring and diagnosis of the steam turbine flow passage is the most important premise to achieve the power plant condition maintenance. The existing characteristic flow area of steam turbine changes with main steam flow and can not accurately reflect the flow passage state of steam turbine. In order to reflect the state change in turbine passage accurately, the characteristic flow area of steam turbine stage should be investigated in the same main steam flow. Because main steam flow on-line measuring method accuracy is deficient, a new method based on the exhaust pressure of IP cylinder as character parameter of main steam flow is proposed, and a correction method which takes the impact of the heat regenerative system on main steam flow into consideration is presented. Meanwhile, in the diagnostic process, the measuring result is strongly influenced by the system inevitable measuring error which directly affects the deviation between the characteristic flow area and its standard. Thus confidence intervals of characteristic flow area is given to eliminate the system errors. Finally, the actual diagnostic example in the article indicates the practicability of the method. It can be used to diagnose the flow passage of steam turbine and provide reliable basis to find out the steam turbine potential.

1. Introduction

Steam turbine throughflow part is the core of the steam turbine, its running state directly affects the safety and economic operation of the steam turbine, especially with the once-through boiler of large capacity and super criticality unit put into operation, increase the difficulty of the boiler water desalination, steam turbine fouling on flow passage is inevitable. Due to poor grid peak valley and the electricity grid stroke unit ratio increasing, the steam turbine start-stop or frequent load change frequently, causing the turbine static and rotational friction, which resulted in increased flow of steam turbine clearance, affects the economy and safety of steam turbine[1,2]. Therefore, research on steam turbine condition monitoring and diagnosis method on flow passage, is significance to identify the running state of the steam turbine in time.

At present, there are many literatures of steam turbine running state monitoring and diagnosis method on flow passage was studied. In the literature [3,4,5,6], fault diagnosis method of turbine flow passage are studied respectively, Which lays an important foundation for improving the safety and economy of the turbine flow passage. In terms of monitoring and diagnosis of scale formation degree in the through-flow part of the steam turbine, the literature [7] conducted a simulation study on the influence of scale
formation in the through-flow part of the steam turbine, and revealed the mechanism of the influence of scale formation in the through-flow part on the safety and economy. In literature [8], whether the pressure in the monitoring section of a steam turbine exceeds 10% of its expected value is used to judge the scaling condition of the flow passage. However, the farther the measuring point of the monitoring section is from the scaling stage, the less sensitive the pressure in the monitoring section is to scaling. In the literature [9], a method for calculating the scale thickness of the through-flow part of a steam turbine is proposed. However, it is difficult to accurately determine the scale thickness proportional coefficient at each level in the actual operation of a steam turbine. In the literature [10], the relationship between scaling in the through-flow part of the steam turbine and the thermodynamic state parameters was established. However, it is necessary to determine the proportional coefficient of scale thickness at all levels and the average thickness of scale thickness in advance, these data are difficult to determine accurately during turbine operation. In literature [11], the diagnosis method of scale formation in the through-flow part of condensing steam turbine is given. Although qualitative analysis of scale formation in the through-flow part of steam turbine is carried out, quantitative diagnosis is not carried out. In literature [12], the concept of characteristic through-flow area of a steam turbine was proposed to reflect the variation of the through-flow area of a steam turbine. However, it is necessary to know the main steam flow rate or the steam flow rate through the stage group, which is difficult to accurately obtain in operation.

In steam turbine clearance diagnosis on flow passage, the on-line monitoring of steam turbine through-flow part of dynamic and static clearance mature methods is not exist. In the process of steam turbine operation, operators often rely on experience by observing steam turbine heat extraction temperature or cylinder exhaust temperature changes in the situation to determine the changes in clearance on flow passage. But in fact, any reason that causes the relative internal efficiency of steam turbine to decrease will cause the temperature of recovery extraction or the temperature of cylinder exhaust to rise, the increased clearance of the passage is only one of the reasons. For all this, the change of the clearance of the turbine flow passage can only be found by the inspection.

For above, this paper first discusses the concept and determination method of characteristic flow area of steam turbine put forward in literature [12]. Then, aiming at the problem that there is no accurate on-line monitoring method for the main steam flow of steam turbine at present, the characteristic parameters of the main steam flow are put forward by using the exhaust pressure of the medium pressure cylinder, and a modified method considering the influence of the regenerative system on the exhaust pressure is put forward. Finally, a method for monitoring and diagnosing the condition of the turbine's through-flow part is presented. The calculation results show that the proposed method is helpful to the early detection and timely treatment of the abnormal operation condition of the turbine flow passage.

2. Analysis of calculation method of characteristic flow area

2.1. The characteristic through-flow area was calculated based on the conventional Flugel formula

For the intermediate stage group of the turbine flow passage part, reference [12] is based on the Flugel formula

\[
F = \frac{G_{1}}{A_{1}} \left( \frac{p_{01}}{p_{0} \sqrt{1 - \pi_{1}^{2}}} \right)^{1/2} \frac{T_{0}}{T_{01}}
\]

The characteristic flow area of the turbine is given as

\[
F = \frac{G_{1} \sqrt{\frac{T_{01}}{T_{0}}}}{p_{01} \sqrt{1 - \pi_{1}^{2}}}
\]

Where: \( G_{0} \), \( G \) the main steam flow rate under the design condition and the actual operation condition respectively, kg/s; \( A_{0} \), \( A \) the through-flow area of the turbine under the design state and the operation state respectively, m\(^2\); \( p_{0} \), \( p_{01} \) the pre-stage pressure under the design condition and the
actual operating condition respectively, MPa; $T_0$, $T_{01}$ the pre-stage temperature under the design condition and the actual operating condition respectively, K; $\pi$, $\pi_1$ the intermediate group pressure ratio under the design condition and the actual operating condition respectively.

For condensing turbines, the extraction pressure before the last stage group is proportional to the steam flow rate, that is

$$\frac{G}{G_0} = \frac{A_0}{A} \frac{p_e}{p_{e0}}$$  \(3\)

where:

$G_0$, $G$ the modification pressure before the last stage group of steam turbine under design state and operation state respectively, MPa.

The characteristic parameters of the area of the flow passage of the last group can be expressed as

$$F = \frac{G}{p_e}$$  \(4\)

Theoretically, the stage group do not change, no matter how the operating conditions and thermal parameters change, the characteristic flow area should remain unchanged. However, it varies greatly with the change of the main steam flow rate. When the main steam flow rate is reduced from the rated flow rate to 30%, the relative change of the characteristic through-flow reaches 7%. Obviously, such a large error results a cannot be used as a parameter to reflect the change of partial area of the flow.

2.2. The characteristic flow area is calculated based on ideal gas Flugel formula

In literature [12], the variation of characteristic through-flow area with the main steam flow rate is attributed to the use of ideal gas in the derivation of Flugel's formula. The steam in the actual steam turbine is assumed to be an ideal gas, so as to obtain the improved Flugel's formula completely based on the ideal gas.

$$\frac{G_0 \sqrt{v_0}}{\sqrt{p_0(1-\pi^2)}} = \frac{G \sqrt{v_{01}}}{\sqrt{p_{01}(1-\pi_1^2)}}$$  \(5\)

Then, another parameter that reflects the characteristic flow area of the turbine is obtained, namely

$$F = \frac{G \sqrt{v_{01}}}{\sqrt{p_{01}(1-\pi_1^2)}}$$  \(6\)

where:

$v_0$, $v_{01}$ the specific capacity of the steam turbine under the design state and before the lower group in the operation state respectively, m$^3$/kg.

For the final stage of condensing turbine, it can also be obtained by the corresponding ideal gas formula[12]. The characteristic through-flow area obtained based on equation (5) has a small change with the main steam flow rate, which can be used to reflect the change through-flow area.

In addition, assuming that the steam is an ideal gas, the pressure ratio before and after the stage group remains unchanged after the working condition changes, which is obviously unreasonable. Especially in the case that the turbine flow area changes, even if the steam flow through the stage group is unchanged, the pressure ratio will change. When calculating the flow area group characteristics at various levels, the main steam flow rate is used to replace the flow rate of each group. In fact, in the process of steam turbine operation, main steam flow is still no accurate online measurement method, the characteristic through-flow area presented in literature [12], Unable to accurately reflect the turbine flow area changes.

3. Improvement of the calculation method of characteristic flow area

The Flugel formula in its derivation, it is not only assumed that the steam is an ideal gas, but also assumed that the reaction degree of operating conditions is unchanged, the sum of pre- and post-stage pressures is much greater than the difference between the two, etc. Therefore, even if the geometric parameters of the stage group do not change, when the operating conditions and thermal parameters change, the characteristic flow area will also change.
In order to make the characteristic through-flow area reflect the variation of the turbine through-flow area, the variation of the characteristic through-flow area of the stage group under the same main steam flow rate should be investigated.

3.1. Characteristic parameters reflecting the main steam flow rate
Considering the actual operation of steam turbine, it is difficult to accurately determine the flow rate, the exhaust pressure of the medium pressure cylinder is less responsive to the state change of the flow passage, the exhaust pressure of the medium pressure cylinder is proportional to the flow rate of the main steam.

\[ G = \alpha p_{mo} \]  

Where: \( \alpha \), the scaling factor; \( p_{mo} \), the exhaust steam pressure of the medium pressure cylinder under running condition, MPa.

3.2. Correction of exhaust pressure of steam turbine medium pressure cylinder
During the operation of steam turbine, when the condition of the regenerative system is abnormal, such as increased pressure loss in the extraction pipeline, heater end difference increases, heater bypass door is not tight, etc, even under the same main steam flow rate, the exhaust pressure of the middle pressure cylinder will be different, so that the exhaust pressure of the middle pressure cylinder cannot accurately reflect the size of the main steam flow rate.

It is stipulated in the thermal test standard (ASME PTC 6-2004) that the state correction of steam turbine recovery system is based on the thermal process line of the test condition, and the steam state expansion line is kept unchanged during the correction process. But because condensing steam turbine exhaust and the last few stages of extraction in the wet steam area, the enthalpy values of extraction and exhaust steam in the wet steam region should be calculated iteratively during the correction process. This will increase the time of system analysis, bring a large error to the correction results.

In order to avoid the difficulty of calculating the enthalpy of steam exhaust and the enthalpy of the most terminal recovery point of steam extraction, the method of parameter correction for thermal system of steam turbine thermal test results is improved. The modified method is based on the isentropic expansion line of steam turbine, the points of intersection between the isentropic expansion process and the corresponding steam extraction pressure are taken, it is convenient to determine the point of heat recovery and steam extraction. The heat recovery and steam extraction of steam turbine during isentropic expansion is determined, then, the modified pre - and post - pressure of the stage group is solved by using Flugel's formula.

Figure 1. Schematic system diagram of 300MW unit
In the figure: ① high-pressure cylinder balance drum steam leakage ② Steam leakage of medium pressure cylinder sleeve ③ Steam leakage in sealing of rear axle of high-pressure cylinder ④ Small steam turbine extraction ⑤ Reheater spray desuperheating ⑥ Steam leakage of shaft seal to shaft seal cooler ⑦ Steam leakage in sealing of rear axle of high-pressure cylinder ⑧ Steam leakage of shaft seal of medium pressure cylinder ⑨ Low pressure cylinder steam supply ⑩ The low pressure cylinder leaks steam. Due to the length of the reason, there are some other small flow rate is not marked.

### Table 1. Results of the modified calculations

| Turbine extraction point | Correction of extraction pressure (MPa) | Absolute error (MPa) | Relative error (%) |
|--------------------------|----------------------------------------|----------------------|-------------------|
|                          | Test expansion line                    | Isentropic expansion line |                   |
| 1                        | 5.530785                               | 5.531287             | -0.000502         | 0.009             |
| 2                        | 3.5706                                 | 3.5706               | 0                 | 0                 |
| 3                        | 1.56285                                | 1.56125              | 0.001725          | 0.110             |
| 4                        | 0.817041                               | 0.817001             | 0.000040          | 0.005             |
| 5                        | 0.321029                               | 0.321185             | -0.000156         | 0.049             |
| 6                        | 0.131323                               | 0.131485             | -0.000162         | 0.123             |
| 7                        | 0.096373                               | 0.096444             | -0.000071         | 0.074             |
| 8                        | 0.019084                               | 0.019092             | -0.000008         | 0.042             |

It can be seen from table 1 that the error of the system correction results based on the actual expansion line and isentropic expansion line is very small, and the relative error does not exceed 0.2%, which meets the requirements of thermal test accuracy.

In this way, the system correction based on isentropic expansion line can guarantee the correctness of the system correction results, the calculation process of system modification avoids the problem of calculating the enthalpy of wet steam, it can not only simplify the calculation steps of the correction process, but also improve the accuracy of the correction results. The steam discharge pressure of the modified medium pressure cylinder can accurately reflect the main steam flow rate.

### 4. A method for diagnosing the part state of steam turbine flow

This method is based on the data obtained from the computer data acquisition system by using the existing conventional measuring points of steam turbine. The core of diagnosis is to obtain the characteristic flow area according to the steam parameters (diagnostic parameters) currently measured in the steam turbine by formula (2) or formula (4), compare it with the standard value under the initial intact condition of the flow section, and determine whether the operation state of the turbine flow section is normal. The initial intact condition refers to the working condition of the steam passage part after the overhaul of the turbine.

However, in the process of diagnosis, the results obtained by measurement are largely affected by the inevitable measurement errors of the system. This error will affect the deviation between the characteristic flow area obtained by measuring the steam parameters (diagnostic parameters) and its standard value.

Because some parameters are neglected in the derivation of feuegel's formula, most of these parameters are related to the steam flow rate through the stage group, so it is also related to the steam flow rate. In order to determine the variation of characteristic through-flow area, the variation area under the same main steam flow rate is used to characterize the variation through-flow part.

Therefore, based on the parameters of the turbine after maintenance, the relationship between the characteristic through-flow area and the characteristic parameters of the main steam flow (i.e. the exhaust pressure of the medium pressure cylinder) is obtained by linear fitting.

\[ F = a p_{m0} + b \]

According to the probability theory [13], when the confidence is 95%:

The upper limit of the confidence interval: \[ F = a p_{m0} + b + 2\sigma \]

The lower limit of the confidence interval: \[ F = a p_{m0} + b - 2\sigma \]
Where:  \( a \), \( b \) the coefficient of linear fitting;  \( \sigma \) the fitted standard variance.

Under the condition that the flow passage part of the turbine is normal, the characteristic flow area value is 95% likely to be between the upper and lower limits for a certain steam flow rate. When the characteristic flow area is above the line, it indicates that the flow area of the turbine increases and the radial clearance of the rotor blade or baffle increases. When the characteristic through-flow area is below the lower line, it indicates that the through-flow area of the steam turbine decreases and the through-flow part of the steam turbine scales.

5. An example of diagnosis of state change in the through-flow part of a steam turbine

5.1. Characteristic through-flow area of steam turbine under intact through-flow condition

For above 300MW steam turbine, The through-flow part of the turbine is divided into nine stages. The high-pressure cylinder is divided into two stages, the first stage of steam extraction and regulation stage after the flow section, the high-pressure cylinder steam exhaust and the first section of steam extraction flow section. The middle pressure cylinder has two stages: the inlet of the middle pressure cylinder and the third stage of the extraction and flow passage, and the exhaust and the third stage of the extraction and flow passage of the middle pressure cylinder. There are 5 stages of the low-pressure cylinder: the fifth stage of extraction and the inlet passage; the sixth stage of extraction and the inlet passage; the seventh stage of extraction and the fifth stage of extraction and the fifth stage of extraction and the fifth stage of extraction and the fifth stage of extraction and the fifth stage of extraction and the seventh stage of extraction and the eighth stage of extraction and the seventh stage of extraction and the seventh stage of extraction and the eighth stage of extraction and the seventh stage of extraction.

(a) Characteristic flow area between the first stage extraction and the high-pressure cylinder exhaust

(b) Characteristic flow area between the third stage of extraction and the middle pressure cylinder

(c) Characteristic flow area between the fifth and seventh extraction stages

(d) Characteristic flow area of the last group (the seventh to the eighth extraction stages)

Figure 2. The Character Flow Area after Overhauling
The relationship between its characteristic through-flow area and steam flow rate is linearly fitted with the data obtained after the overhaul of the unit, and the upper and lower limits of its characteristic through-flow area are obtained as shown in Figure 2.

5.2. Verification of the correctness of the monitoring and diagnosis method for the pass-through part
In order to verify the correctness of the upper and lower limits of the obtained characteristic through-flow area, the corresponding relationship between the obtained characteristic through-flow area and steam flow rate in the normal operation of the turbine is listed in Figure 3, the upper and lower line is still obtained from the data of the unit after maintenance.

As can be seen from Figure 3., under the condition of normal flow area of steam turbine, more than 95% of the values of characteristic flow area are between the upper and lower limits, which proves the effectiveness of establishing characteristic flow area with the data after overhaul.

5.3. Monitor and diagnose the state of the flow passage during operation
Using the operation data of a certain period of time after 2 years of operation after overhaul of steam turbine, the characteristic flow area of corresponding groups is calculated, and the relationship between it and characteristic parameters of main steam flow is shown in Figure 4.

As Figure 4, Characteristic flow area between the first stage of extraction and the high-pressure cylinder exhaust, the characteristic flow area of the stage group between the third stage of extraction and the middle pressure cylinder, the Characteristic flow area between the fifth and seventh extraction stages is between the upper and lower limits, shows that the flow area of these stages is in the normal range. But, More than 50% of the points of Characteristic flow area of the last group are above the upper
limit, indicates that the flow area of this stage group is larger. Considering that the possibility of corrosion of the flow passage part of modern large steam turbine is very small, it is judged that the radial clearance between the dynamic and dynamic parts of the steam turbine becomes larger.

![Graphs showing flow area comparison](image)

(a) Characteristic flow area between the first stage extraction and the high-pressure cylinder exhaust  
(b) The characteristic flow area between the third stage extraction and the middle pressure cylinder  
(c) Characteristic flow area between the fifth and seventh extraction stages  
(d) Characteristic flow area of the last group (the seventh to the eighth extraction stages)

**Figure 4. The Character Flow Area in Diagnostic Process**

At present, the problem of low pressure exhaust cylinder deformation exists in all 300MW steam turbines to different degrees, and this problem also exists in this steam turbine, which causes the flow area of the last stage group of the steam turbine to increase, the actual maintenance process also proved this point.

### 6. Conclusion

Frugal formula is an approximate formula obtained on the basis of a large number of assumptions, the characteristic flow area of the stage group based on it is actually a parameter related to the main steam flow rate, which cannot directly reflect the change of the turbine flow area.

Reflecting the change of the through-flow area of the turbine accurately, the change of the characteristic through-flow area under the same main steam flow rate should be used to reflect the change of the through-flow area.

Online measuring the main steam flow accurately is rather difficult. The steam discharge pressure of the medium pressure cylinder after the state of the regenerative system to reflect the main steam flow and calculate the characteristic flow area of each group is proposed, and the characteristic flow area of each group is calculated.
The characteristic flow area calculation method is presented in this paper, achieves the early detection of the abnormal state of the turbine flow passage functional, meanwhile provides an online supervision method for safe and economical operation of steam turbine.

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