Study on a New Method of Determining Boiler Soot-blowing Steam Flow Rate

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Abstract. In this paper, a new method of determining boiler soot-blowing steam flow rate was proposed. By this method, three tests of unaccounted-for leakage rate of the unit thermal system should be conducted without soot blowing, and the unaccounted-for leakage ratio difference between arbitrary two tests should be within 0.10%. The average value of three unaccounted-for leakage flow rate test results was used as the final result of unit unaccounted-for leakage flow to determine the flow rate of soot-blowing steam. During the test period of power output and heat rate, the calculation of soot blowing steam flow rate took account of the result of unaccounted-for leakage tests and the water level change of condenser hot well, deaerator and boiler drum.

1. Introduction
The steam turbine performance test was the most effective method to determine the power output and heat rate of the power unit with the highest accuracy at present. The corresponding performance test was conducted according to the international standard ASME PTC 6-2004 Steam Turbines Performance Test Code, by which, the unit power output and heat rate test uncertainty could be within 0.25% [1]. The unaccounted-for leakage rate of the unit thermal system had an important influence on the test results of the unit power output and heat rate [2]. In the uncertainty analysis of the turbine performance test results, the sensitivity coefficient of the unaccounted-for leakage rate in the uncertainty calculation of test results was up to 1.0%/%, which meant that the uncertainty of the heat rate test result caused by the unaccounted-for leakage rate was a% when the unaccounted-for leakage rate of the thermal system was a% [3]. In the actual operation of the unit, because of poor-quality coal or equipment fault, the boiler soot-blowing steam could not be completely isolated, it was necessary to determine the flow rate of soot-blowing steam during the performance test period [4]. Furthermore, because the pressure of soot blowing steam passing through the orifice plate varied greatly and the flow rate of soot-blowing steam was unstable, the direct measurement for the soot-blowing steam flow rate could produce larger errors. This paper proposed a new method, which could provide a relatively accurate boiler soot-blowing steam flow rate with a lower uncertainty.

2. Principle and processing flowchart of the method
In the case of isolation and no soot blowing, if the thermal system isolation was as consistent as possible, the unaccounted-for leakage flow rate of the thermal system should be the same every time. The processing flow chart of the new method of determining boiler soot-blowing steam flow rate was presented in Figure 1.
2.1. Calculation of unaccounted-for leakage flow rate without soot blowing

The calculation formula of unaccounted-for leakage flow rate without soot blowing was as follows.

$$\Delta F_i = F_{hv l} + F_{dl} + F_{drum} - F_{ml}$$  (1)

where $\Delta F_i$ was the result of the test $i$ for the unaccounted-for leakage flow rate, t/h; $F_{hv l}$ was the equivalent flow rate of hot well level change, t/h; $F_{dl}$ was the equivalent flow rate of deaerator water.
tank level change, t/h; \( F_{\text{drum}} \) was the equivalent flow rate of boiler drum water tank level change, t/h; \( F_{\text{ml}} \) was the measured leakage flow of the cycle, t/h.

2.2. Unaccounted-for leakage of thermal cycle system
Unaccounted-for leakage flow rate without soot blowing was acquired through 3 separate unaccounted-for leakage flow rate tests. The calculation formula of unaccounted-for leakage flow rate of thermal system was as follows.

\[
\Delta F = \frac{\Delta F_1 + \Delta F_2 + \Delta F_3}{3}
\]  

where \( \Delta F \) was the thermal cycle system unaccounted-for leakage flow rate, t/h; \( \Delta F_1 \) was the first test result of unaccounted-for leakage flow rate tests, t/h; \( \Delta F_2 \) was the second test result of unaccounted-for leakage flow rate tests, t/h; \( \Delta F_3 \) was the third test result of unaccounted-for leakage flow rate tests, t/h.

2.3. Calculation of soot blowing steam flow rate
The calculation formula of the boiler soot blowing steam flow rate of thermal system was as follows.

\[
F_s = F_{\text{hwl}} + F_{\text{dl}} + F_{\text{drum}} - F_{\text{ml}} - \Delta F
\]  

where \( F_s \) was the boiler soot blowing steam flow rate, t/h; \( \Delta F \) was the thermal cycle system unaccounted-for leakage flow rate without soot blowing, t/h; \( F_{\text{hwl}} \) was the equivalent flow rate of hot well level change, t/h; \( F_{\text{dl}} \) was the equivalent flow rate of deaerator water tank level change, t/h; \( F_{\text{drum}} \) was equivalent flow rate of boiler drum water tank level change, t/h; \( F_{\text{ml}} \) was measured leakage flow of cycle, t/h.

2.4. Calculation of the equivalent flow rate of vessel level change
The equivalent flow rate was defined to be positive when the vessel level went down, while oppositely it was defined to be negative. The calculation formula of equivalent flow rate of vessel level change was as follows.

\[
F_i = \frac{(V_{H2} - V_{H1}) \times \rho_i}{\Delta t}
\]  

where \( F_i \) was the equivalent flow rate caused by the level change of vessel \( i \), t/h; \( V_{H2} \) was the start water level of vessel \( i \), m\(^3\); \( V_{H1} \) was the end water level of vessel \( i \), m\(^3\); \( \rho_i \) was the mean water density in vessel \( i \), kg/m\(^3\); \( \Delta t \) was the test time-period, h.

The volume calculation formula of the deaerator and boiler drum water tank was as follows.

\[
V_L = M \times \left[ H \times \sqrt{R^2 - H^2} + R^2 \times \arctan \left( \frac{H}{\sqrt{R^2 - H^2}} \right) \right] + \pi \times (R \times S \times H - \frac{S \times H^3}{3 \times R})
\]  

where \( V_L \) was the water volume of deaerator or boiler drum water tank, m\(^3\); \( H \) was the water level of deaerator or boiler drum water tank, m; \( M \) was the length of the cylindrical section of the deaerator or boiler drum water tank, m; \( S \) was the ellipsoidal plug height of deaerator or boiler drum water tank,
m; $R$ was the cylindrical radius of deaerator or boiler drum water tank, m. These dimensions are shown in Figure 2.

![Figure 2. Schematic diagram of deaerator or boiler drum water tank.](image)

The hot well could be approximated to be a cube. The calculation formula for its volume was as follows.

$$V_L = N \times W \times H$$

(6)

where $V_L$ was the water volume of hot well, m$^3$; $H$ was water level of hot well, m; $N$ was the hot well length, m; $W$ was the hot well width, m.

3. Application examples of the method

The performance test for PAMPA SUL Coal Fired Power Plant in Brazil was taken as an example. The PAMPA SUL Coal Fired Power Station project is located in the city of Candiota council in state of Rio Grande do Sul, which is in the southern region of Brazil about 80 km from the city of Bagé, 5 km at the South of the road BR-293, close to the Uruguay border. The project constructed a 345MW coal fired facility, which was contracted by Shandong Ludian International Technology and Trade CO., LTD from China.

3.1. Main technical data of PAMPA SUL coal fired power plant

3.1.1. Main technical data for steam turbine. The steam turbine main technical data was listed in Table 1.

| Item | Unit | Detail |
|------|------|--------|
| Unit output | MW | 345 |
| Steam turbine type | / | Sub-critical, single reheat, combined HP/IP-turbine, double-flow LP-turbine |
| Operation pressure at main steam (HP) emergency stop and control valve inlet | MPa(a) | 16.67 |
| Operation temperature at main steam (HP) emergency stop and control valve inlet | ℃ | 538.0 |
| Operation pressure of cold reheat steam | MPa(a) | 4.7 |
| Operation temperature of cold reheat steam | ℃ | 347.0 |
| Operation pressure at combined reheat steam (IP) emergency stop and control valve inlet | MPa(a) | 4.26 |
| Operation temperature at combined reheat steam (IP) emergency stop and control valve inlet | ℃ | 538.0 |
| Number of extractions | / | 8 |
| Average back pressure | kPa(a) | 5.8 |
| Feed water temperature (TMCR condition) | ℃ | 285.0 |
| Rated speed | 3600r/min |

3.1.2. Main technical data for boiler. The boiler main technical data was listed in Table 2 [5].
Table 2. Main technical data for boiler.

| Item                      | Unit | BMCR       | TMCR       | 40%BMCR   | 40%TMCR   |
|---------------------------|------|------------|------------|-----------|-----------|
| Main steam flow rate      | t/h  | 1116.30    | 1063.16    | 432.85    | 415.02    |
| Main steam pressure       | MPa(g) | 17.400    | 17.400    | 6.970     | 7.010     |
| Main steam temperature    | °C   | 541.0      | 541.0      | 541.0     | 541.0     |
| Feedwater temperature     | °C   | 286.0      | 283.0      | 235.0     | 233.0     |
| Spray water temperature   | °C   | 193.0      | 191.0      | 157.0     | 155.0     |
| Reheat steam flow rate    | t/h  | 938.222    | 896.526    | 376.413   | 361.5     |
| Reheater inlet pressure   | MPa(g) | 4.588     | 4.383      | 1.818     | 1.737     |
| Reheater outlet pressure  | MPa(g) | 4.398     | 4.202      | 1.740     | 1.662     |
| Reheater inlet temperature| °C   | 345.8      | 344.0      | 355.7     | 355.0     |
| Reheater outlet temperature| °C   | 541.0      | 541.0      | 541.0     | 541.0     |

3.2. Key dimensions of the vessels

The key dimensions of the hot well, the deaerator and the boiler drum water tank were shown in Table 3.

Table 3. Key dimensions of the vessels.

| Item              | Unit | Length | Width | Cylinder section length | Cylindrical radius |
|-------------------|------|--------|-------|-------------------------|-------------------|
| Hot well          | m    | 12.5   | 8.1   | /                       | /                 |
| Deaerator         | m    | 21.2   | /     | 21.0                    | 2.0               |
| Boiler drum water tank | m    | 20.0   | /     | 12.5                    | 1.0               |

3.3. Test results of unaccounted-for leakage flow rate tests without soot blowing steam

The main test results of unaccounted-for leakage flow rate tests without using steam for soot blowing under TMCR condition were listed in Table 4. TMCR condition refers to turbine maximum continue rate condition.

Table 4. Main test results for unaccounted-for leakage flow rate tests without soot blowing steam.

| Test condition                                          | Unit | TEST-1       | TEST-2       | TEST-3       |
|--------------------------------------------------------|------|--------------|--------------|--------------|
| Test data                                              | y/m/d | 2019/12/16   | 2019/12/16   | 2019/12/16   |
| Test start time                                        | h:m  | 09:40        | 14:30        | 20:40        |
| Test end time                                          | h:m  | 10:40        | 15:30        | 21:40        |
| Generator terminal power output                       | MW   | 345.248      | 345.231      | 345.243      |
| Steam drum pressure (a)                                | MPa  | 18.241       | 18.640       | 18.720       |
| Deaerator pressure (a)                                 | MPa  | 1.262        | 1.266        | 1.264        |
| Hot well water temperature                             | °C   | 39.0         | 39.1         | 39.0         |
| Mainsteam flow rate                                    | t/h  | 1078.776     | 1083.179     | 1082.371     |
| Deaerator start water level                            | mm   | 2826.4       | 2820.1       | 2823.7       |
| Deaerator end water level                              | mm   | 2825.9       | 2820.4       | 2823.6       |
| Hot well start water level                             | mm   | 844.2        | 840.1        | 849.3        |
| Hot well end water level                               | mm   | 797.2        | 790.7        | 798.1        |
| Boiler drum start water level                          | mm   | 396.1        | 396.4        | 396.3        |
| Boiler drum end water level                            | mm   | 396.2        | 395.8        | 395.9        |
| Boiler drum water density                              | kg/m³ | 538.8       | 529.8        | 528.0        |
| Deaerator water density                                | kg/m³ | 875.8       | 875.6        | 875.7        |
| Hot well water density                                 | kg/m³ | 992.6       | 992.6        | 992.6        |
| Equivalent flow rate of deaerator water level change   | t/h  | 0.035        | -0.021       | 0.007        |
| Equivalent flow rate of boiler drum water level change | t/h  | -0.003       | 0.017        | 0.011        |
| Equivalent flow rate of condenser hot well water level change | t/h  | 4.722        | 4.965        | 5.143        |
| Unaccounted-for leakage mass flow rate without soot blowing steam | t/h  | 4.754        | 4.960        | 5.143        |
| Unaccounted-for leakage mass flow rate average value without soot blowing steam | t/h  | 4.958        |               |              |
3.4. Test results of soot blowing steam flow rate
Under the TMCR-1 condition, the measured generator power output is 344.894MW, the main steam mass flow rate is 1089.342t/h, the soot blowing mass flow rate is 6.917t/h. Under the TMCR-2 condition, the measured generator power output is 344.989MW, the main steam mass flow rate is 1092.447t/h, the soot blowing mass flow rate is 6.668t/h. The main test results of soot blowing steam flow rate tests under TMCR condition were listed in Table 5.

Table 5. Main test results for soot blowing steam flow rate tests.

| Test condition                        | Unit | TMCR-1 | TMCR-2 |
|---------------------------------------|------|--------|--------|
| Test data                             | y/m/d|        |        |
| Test start time                       | h/m  | 11:00  | 20:10  |
| Test end time                         | h/m  | 15:30  | 22:00  |
| Generator terminal power output       | MW   | 344.894| 344.989|
| Steam drum pressure (a)               | MPa  | 17.299 | 17.241 |
| Deaerator pressure (a)                | MPa  | 1.328  | 1.330  |
| Hot well water temperature            | °C   | 38.8   | 38.6   |
| Mainsteam flow rate                   | t/h  | 1089.342| 1092.447|
| Deaerator start water level           | mm   | 2850.3 | 2856.8 |
| Deaerator end water level             | mm   | 2842.4 | 2846.1 |
| Hot well start water level            | mm   | 964.3  | 1030.8 |
| Hot well end water level              | mm   | 438.0  | 573.5  |
| Boiler drum start water level         | mm   | 395.7  | 391.5  |
| Boiler drum end water level           | mm   | 396.0  | 398.8  |
| Boiler drum water density             | kg/m³| 537.5  | 538.8  |
| Deaerator water density               | kg/m³| 873.2  | 873.1  |
| Hot well water density                | kg/m³| 992.6  | 992.7  |
| Equivalent flow rate of deaerator water level change | t/h | 0.123 | 0.187 |
| Equivalent flow rate of boiler drum water level change | t/h | -0.002 | -0.051 |
| Equivalent flow rate of condenser hot well water level change | t/h | 11.755 | 11.491 |
| Total unaccounted-for leakage mass flow rate with soot blowing steam | t/h | 11.875 | 11.626 |
| Unaccounted-for leakage rate based on main steam mass flow without soot blowing steam of the thermal system | t/h | 4.958 | 4.958 |
| Soot blowing steam flow rate          | t/h  | 6.917  | 6.668  |

4. Test uncertainty analysis
With the continuous improvement of measurement accuracy, the current industrial water level gauge measurement accuracy is high enough. As the accuracy of the single unaccounted-for leakage test of the thermal system proposed in this paper was within 0.1% of the main steam flow, the repeatability requirements should be met between the three tests. The average value of the three test results was used as the unit unaccounted-for leakage to calculate the soot blowing steam flow. As long as the test duration was long enough to avoid the additional error caused by the water level fluctuation of the thermal system water storage container, the uncertainty of soot blowing flow rate obtained would not be greater than 0.1% of the main steam flow [6].

5. Summary
In this paper, a new method of determining boiler soot-blowing steam flow rate was proposed and presented, which provided an approach to conduct steam turbines performance test without isolating boiler soot-blowing steam. According to this method, three tests of the unit thermal system unaccounted-for leakage rate without soot blowing were conducted to obtain the value of the unit thermal system unaccounted-for leakage rate under the condition of no soot-blowing. When the
thermal system isolation was as consistent as possible, the unaccounted-for leakage flow rate of the thermal system without soot blowing should be the same every time. Then, after having performed the test of soot blowing steam flow rate, we could obtain a total unaccounted-for leakage mass flow rate containing soot blowing steam. Thus, the boiler soot-blowing steam flow rate was obtained by subtracting the unit thermal system unaccounted-for leakage rate without soot blowing from the total unaccounted-for leakage mass flow rate containing soot blowing steam. This new method could provide a relatively accurate boiler soot-blowing steam flow rate with a lower uncertainty, which made the whole uncertainty of performance test to be more effectively controlled.

References

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