Energy and Exergy Analysis of Steam Source Optimization for Boiler Soot Blowing System

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Abstract. In order to improve the economy of boiler soot blowing system, the steam source position of boiler soot blowing system should be optimized. For a 1000MW ultra-supercritical coal-fired unit, the thermodynamic process of soot blowing steam in temperature and pressure reducing station was studied through energy analysis and exergy analysis in this paper, and it was revealed that the annual water and energy consumption of boiler soot blowing system was independent of the steam source position, the change of steam source position only affected the annual exergy loss of soot blowing system. The comparison results indicated that the annual exergy loss of soot blowing system with cryogenic reheater outlet as steam source was minimal. After adopting cryogenic reheater outlet as the steam source position of soot blowing system, it would be more economical than the original soot blowing system with platen superheater outlet as steam source. The annual exergy loss would be reduced by about $2.183 \times 10^{10}$ kJ, and it was equivalent to an annual increase of power generation revenue by about 2486000 CNY.

1. Introduction

Steam soot blowing is widely adopted to clean the fly ash adhering to heating surface during the operation of utility boilers due to high efficiency and strong coal adaptability. The steam employed is generally taken from the outlet header of the boiler's platen superheater, which will cause large energy loss when blew into furnace in view of its high temperature and pressure. Therefore, in order to enhance the operation economy of the boilers, some power plants have already decreased the quality of soot-blowing steam and thereby the energy loss by optimizing the steam source positions of steam soot blowing [1]. However, when analyzing the economy of steam soot blowing with steam from different source positions, power generation enterprises either simply compared the steam enthalpy at different steam source positions and calculated the economic benefits by the enthalpy difference after optimizing the steam source positions [2], or simply compared the steam exergy at different steam source positions and calculated by the exergy difference after optimizing the steam source positions, but did not throughly analyze the thermodynamic process of soot-blowing steam in temperature and pressure reducing station, and thus neglected the influence of the desuperheating water there on the economy of soot-blowing steam. As a result, they are unable to measure the economic benefits of steam at the steam source comprehensively.
2. Boiler and Soot Blowing System

The boiler of a 1000MW ultra-supercritical generator is DG3060/27.46-π1 converter DC furnace manufactured by Dongfang Boiler Works and its design parameters are illustrated in Table 1. According to the requirements of soot blowers, the steam pressure and temperature should be controlled at about 2 MPa and 350 ℃ respectively after the steam passes through the temperature and pressure reducing station. Meanwhile, the total soot-blowing steam consumption of the boiler is about 117800 tons per year based on statistics.

| Table 1 The designed steam parameters |
|-------------------------------------|
| Name                                | Unit | BMCR | BRL | THA 75%THA | 50%THA |
| Outlet pressure of platen superheater | MPa  | 27.74| 27.60| 25.93 | 19.08 | 12.64 |
| Inlet pressure of superheater       | MPa  | 4.97 | 4.71 | 4.47 | 3.31 | 2.21 |
| Outlet pressure of cryogenic reheater| MPa  | 4.88 | 4.63 | 4.40 | 3.27 | 2.19 |
| Outlet pressure of high temperature reheater | MPa  | 4.77 | 4.53 | 4.31 | 3.22 | 2.17 |
| Outlet temperature of platen superheater | ℃ | 549 | 548 | 547 | 541 | 544 |
| Inlet temperature of superheater    | ℃  | 344 | 341 | 343 | 349 | 356 |
| Outlet temperature of cryogenic reheater | ℃ | 508 | 508 | 510 | 514 | 526 |
| Outlet temperature of high temperature superheater | ℃ | 603 | 603 | 603 | 603 | 603 |

3. Optimization of steam source in soot blowing system

In order to improve the economy of the boiler, the positions of the soot-blowing steam source can be optimized by using the steam somewhere else instead of from the outlet header of the platen superheater. In this study, the platen superheater outlet, the reheater inlet, the cryogenic reheater outlet and the high temperature reheater outlet are selected as four alternative steam source positions. The parameters of steam at these positions in temperature and pressure reducing station are analyzed, and the effect of desuperheating water on the economy of soot blowing is considered comprehensively so as to obtain the most economical and reasonable soot blowing steam source position.

3.1. Energy Analysis of Soot Blowing System

| Table 2 The specific enthalpy of steam with different source positions |
|---------------------------------------------------------------|
| Working conditions | Steam specific enthalpy of platen superheater outlet (kJ/kg) | Steam specific enthalpy of reheater inlet (kJ/kg) | Steam specific enthalpy of cryogenic reheater outlet (kJ/kg) | Steam specific enthalpy of high temperature reheater outlet (kJ/kg) |
| BMCR               | 3303.57                                                      | 3053.99                                                      | 3454.46                                                      | 3675.63                                                      |
| BRL                | 3301.84                                                      | 3052.67                                                      | 3457.22                                                      | 3677.54                                                      |
| THA                | 3318.49                                                      | 3064.07                                                      | 3464.36                                                      | 3679.29                                                      |
| 75%THA             | 3380.08                                                      | 3106.74                                                      | 3485.65                                                      | 3687.90                                                      |
| 50%THA             | 3459.42                                                      | 3146.71                                                      | 3523.68                                                      | 3696.13                                                      |
Fig. 1 presents the process of steam from different steam source positions changing into soot-blowing steam with specific parameters through temperature and pressure reducing station. First, steam from steam source throttles and decompresses by passing through electric pressure reducing valve M1, and then mixes with desuperheating water to reduce temperature. Next, temperature meters and pressure gauges installed in the tail pipe of temperature and pressure reducing station send back the steam temperature and pressure massages to computer. By calculating and controlling the opening of electric pressure reducing valve M1 and desuperheating water flow control valve M2, the required parameters of soot blowing steam can be attained ultimately. Under different typical working conditions, the steam pressure and temperature at the four positions, i.e., the platen superheater outlet, the reheater inlet, the cryogenic reheater outlet and the high temperature reheater outlet can be acquired from steam design parameters as shown in Table 1. When combining these parameters with IAPWS-IF97 (Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam)[3], the specific enthalphy of steam at each position can also be calculated as shown in Table 2.

Clearly, it can be seen from Table 2 that the steam specific enthalphy at the reheater inlet is the lowest under each typical working condition, based on which some power generation enterprises considered the reheater inlet as the most energy-saving soot-blowing steam source position [2]. In fact, there is mixing of desuperheating water into soot-blowing steam in temperature and pressure reducing station, so the amount of the steam out of the temperature and pressure reducing station is unequal to that from the steam source position. Therefore, the conclusion drawn by the above-mentioned enterprises is inaccurate exactly. Here, the temperature and pressure reducing station is taken as a volume-controlled open system, as surrounded by black dotted lines in Fig. 1. Eq. (1) shows the general expression of the energy equation of this system. Due to the steady flow in the system and the favorable thermal insulation, the variation of the total storage energy of the system and the heat transfer between the system and the outside can be neglected. Additionally, the system has no external work and the variations of the steam mechanical energy can be also neglected, so Eq. (1) can be simplified into Eq. (2) and then rewritten to Eq. (3). Based on the technical specifications of the steam soot blower in power plants, the temperature and pressure of the steam entering soot blowers is usually controlled at 350°C and 2 MPa by operators. Thus, the temperature and pressure of the soot-blowing steam at the outlet of temperature and pressure reducing station and the annual statistical consumption of the soot-blowing steam in power plants can be determined, then \( m_{\text{out}} \) and \( h_{\text{out}} \) in the right of Eq. (3) are stable, which means the annual consumption and energy consumption of soot-blowing steam are both independent with the position of soot-blowing steam source. Therefore, the variation of soot-blowing steam source position could not change annual water and coal consumptions caused by boiler soot blowing.

\[
\dot{Q} = \frac{dE_{CV}}{d\tau} + \sum (h_{\text{out}} + \frac{1}{2} c_{\text{out}}^2 + g z_{\text{out}}) m_{\text{out}} - \sum (h_{\text{in}} + \frac{1}{2} c_{\text{in}}^2 + g z_{\text{in}}) m_{\text{in}} + \dot{W}
\]

(1)

\[
0 = h_{\text{out}} m_{\text{out}} - (h_{w} m_{w} + h_{s} m_{s})
\]

(2)

\[
m_{s} h_{s} + m_{w} h_{w} = m_{\text{out}} h_{\text{out}}
\]

(3)

3.2. Analysis of Soot Blowing System

Although the variation of soot-blowing steam source position could not change annual water and coal consumptions caused by boiler soot-blowing, the quality of the incoming steam used for producing soot-blowing steam is different due to the distinct steam parameters at each steam source position. The aim of optimizing the position of soot-blowing steam source is to use the lower quality incoming steam for producing soot-blowing steam as far as possible, by which the higher quality steam can be conserved for power generation. Compared with energy analysis, exergy analysis can acquire more information about the energy utilization of the system, evaluate the energy loss from the perspective of energy quality and then provide effective ways to reduce the energy loss[4, 5, 6, 7]. Liu et al. [8] tried to study the influence of soot-blowing steam source position on the benefits of power plants by exergy
analysis, but the effect of the desuperheating water in temperature and pressure reducing station was neglected, so the calculated economy benefit of power plant is inaccurate.

The incoming steam from the steam source has undergone two thermal processes in temperature and pressure reducing station. As illustrated in Fig.1, one is throttling through the pressure reducing valve M1 and the other is cooling by mixing with the desuperheating water. During the throttling process, the steam pressure at the outlet of the pressure reducing valve drops to 2 MPa. Since the throttling can be regarded as constant enthalpy process, the temperatures of the steam from the four source positions after throttling and decompression can be obtained according to the IAPWS-IF97. As shown in Table 3, in most cases, the temperature of incoming steam from reheater will be lower than 350°C after throttling, which can not satisfy the temperature requirement of the soot-blowing steam. Therefore, the inlet of reheater is not a suitable place of soot-blowing steam source. Instead, the temperatures of the steam from the outlet of the platen superheater, the cryogenic reheater and the high temperature reheater are all more than 350°C after throttling, and thereby they could be qualified as soot blowing steam only after mixed with the desuperheated water in the temperature and pressure reducing station. The temperature and pressure of the desuperheating water are 180°C and 11 MPa respectively, and the temperature and pressure of soot-blowing steam at the outlet of temperature and pressure reducing station are 350°C and 2 MPa respectively.

**Table 3** The temperature of steam with different source positions after throttling

| Working conditions | Steam temperature of platen superheater outlet after throttling (°C) | Steam temperature of reheater inlet after throttling (°C) | Steam temperature of cryogenic reheater outlet after throttling (°C) | Steam temperature of high temperature reheater outlet after throttling (°C) |
|-------------------|-------------------------------------------------|---------------------------------|-----------------------------------|-----------------------------------|
| BMCR              | 425.19                                          | 312.91                          | 493.82                            | 593.29                            |
| BRL               | 424.40                                          | 312.33                          | 495.07                            | 594.14                            |
| THA               | 431.98                                          | 317.33                          | 498.31                            | 594.92                            |
| 75%THA            | 460.03                                          | 336.19                          | 507.95                            | 598.75                            |
| 50%THA            | 496.07                                          | 354.07                          | 525.14                            | 602.41                            |

The following equations can be used to express the exergy balance of steam from the outlets of the platen superheater, the cryogenic reheater and the high temperature reheater when passing through temperature and pressure reducing station[4].

\[
E_{x,Q} + E_{x,W} = \sum m_{out}e_{out} - \sum m_{in}e_{in} + \sum E_{x,d} \tag{4}
\]

The temperature and pressure reducing station can be regarded as an adiabatic system and does not have external work, so according to Fig.1, Eq. (4) can be rewritten to Eq. (5):

\[
m_1e_{x_1} + m_u e_{x_u} - m_{out} e_{x_{out}} = E_{x_{d1}} + E_{x_{d2}} \tag{5}
\]

Where \(E_{x_{d1}}\) and \(E_{x_{d2}}\) are the exergy losses of the throttling process and the mixing process of steam with desuperheated water respectively.

For the open flow stabilization system, the specific exergy of working fluid can be expressed as:

\[
e_{x} = (h - h_0) - T_0(s - s_0) \tag{6}
\]

where \(e_x\), \(h\) and \(s\) are the specific exergy, the specific enthalpy and the specific entropy of working fluid respectively, subscript 0 denotes the ambient condition, and the specific enthalpy \(h_0\) is 84.01 kJ/kg, and the specific entropy is 0.2965 kJ/(kg·°C) for liquid water at ambient condition.

The specific entropies of the steam at the outlet of the platen superheater, the cryogenic reheater and the high temperature reheater can be calculated through the corresponding steam temperature and pressure and the IAPWS-IF97, and then the specific exergy of the steam at these positions can be calculated according to Eq. (6) and the data in Table 2, which are shown in Table 4. The specific
The specific exergy of steam with different source positions

| Working conditions | Steam specific exergy of platen superheater outlet (kJ/kg) | Steam specific exergy of reheater inlet (kJ/kg) | Steam specific exergy of the cryogenic reheater outlet (kJ/kg) |
|--------------------|----------------------------------------------------------|-----------------------------------------------|-----------------------------------------------------------|
| BMCR               | 1518.70                                                  | 1401.13                                       | 1540.98                                                   |
| BRL                | 1517.03                                                  | 1395.97                                       | 1535.41                                                   |
| THA                | 1520.78                                                  | 1393.79                                       | 1529.98                                                   |
| 75%THA             | 1524.95                                                  | 1368.09                                       | 1496.93                                                   |
| 50%THA             | 1525.75                                                  | 1338.84                                       | 1449.67                                                   |
3.3. Economic Analysis of Soot Blowing System

According to the energy analysis, the variation of soot-blowing steam source position do not change annual water and coal consumptions caused by boiler soot blowing, and thereby the annual average material costs of the steam soot blowing systems. Moreover, according to the exergy analysis, the total exergy loss of soot blowing system with the outlet of cryogenic reheater as the steam source is the smallest among the three types of steam soot blowing system. Since the equal quality of exergy and power[6, 7], the smaller total exergy loss of the soot blowing system means that more exergy can be conserved to convert into electric energy, which brings the greater power generation benefits. Therefore, the soot blowing system with the outlet of cryogenic reheater as the steam source has the greatest power generation benefits.

The unit considered in this paper runs at 75% THA for most of the year, the data under 75% THA are used to calculate and compare the economy of different soot blowing systems. Compared with the original soot blowing system (with platen reheater outlet as steam source), the total exergy loss of soot blowing system with cryogenic reheater outlet as steam source is reduced by $2.183 \times 10^{10}$ kJ, which could increase the generating capacity by $6.064 \times 10^6$ kW·h. For instance, taking the grid purchase price $0.41$ CNY/(kW·h) of coal-fired units in a province in 2018 as the pricing standard, the increased generating capacity is worth about 2486 000 CNY. Therefore, if the steam source position of soot-blowing system is changed from platen reheater outlet to cryogenic reheater outlet, there is an increase of annual average power generation benefits about 2486 000 CNY without changing the annual average cost of raw materials consumed by the soot blowing system.

4. Conclusions

In view of a 1000MW ultra-supercritical coal-fired unit, this work studies the thermodynamic process of soot-blowing steam in the temperature and pressure reducing station through energy analysis and exergy analysis, and conclusions can be drawn as follows:

(1) The annual raw material cost of the steam soot blowing system is independent with the soot blowing steam source position.

(2) For the same soot blowing system, with the decrease of boiler load, the mixing ratio of desuperheating water increases while the annual total exergy loss caused by steam soot blowing decreases. Besides, the total exergy loss of soot blowing systems using the outlet of cryogenic temperature reheater as the steam source are minimal in the three types of steam soot blowing systems.

(3) After changing the steam source position of soot blowing system from platen superheater outlet to cryogenic reheater outlet, there is an increase of annual average power generation benefits about 2486 000 CNY without changing the annual average cost of raw materials consumed by the soot blowing system.

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