Analysis of influence of peak regulation on life of once-through boiler

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Abstract. In this paper, a 670 MW once-through boiler of a power plant is taken as the analysis object. The method of ANSYS numerical analysis is used to calculate the stress of the once-through boiler in different starting modes and different peaking depths. We calculate the life loss of different operating conditions according to the stress value, which provides reasonable suggestions for the life management of the once-through boiler during peak shaving, which can reduce the impact of peak shaving on boiler life.

1. Introduction
In the future, with the continuous expansion of the scale of new energy power generation, thermal power will play a major role in peaking the power grid. When coal-fired units participate in peak shaving, the load often changes rapidly and the unit starts and stops frequently, which will adversely affect the life of the boiler.

The steam-water separator is one of the main pressure-bearing components in the once-through boiler, and is the hub of the boiler steam-water system. If the steam-water separator is damaged during operation, the repair is extremely difficult. Therefore, the study of the effect of peak regulation on boiler life can be based on the study of steam-water separators.

2. Research object
The research object of this paper is a 670MW ultra-supercritical unit of a power plant with the boiler type SG-1978/29.3-M6012. The dimensions of the steam separator and material properties are shown in Tables 1 and 2.

| Table 1. Steam-water separator structure size |
| Part name                          | Pipe diameter |
|-------------------------------------|---------------|
| Cylinder                           | φ610mm×75mm   |
| Soda water introduction tube       | φ170×35       |
| Steam extraction tube              | φ334×55       |
| Water extraction tube              | φ324×5        |
Due to the limited computing ability of the computer, the steam-water separator are simplified:

1. The steam-water separator is a three-dimensional solid structure with bilateral symmetry. It is ok to take 1/2 structure for calculation.

2. This paper mainly studies the position of the dangerous point and the law of stress change during the peak load and start-up process of the low load operation of steam-water separator. The maximum stress is near the tube introduction tube, so in order to save the calculation time, the calculation model is as shown in Figure 1 and 2.

### Tables 2. Physical properties of WB36 steel

| Steel temperature (°C) | Thermal Conductivity (W/m·°C) | Specific heat capacity (KJ/(kg·K)) | Elastic Modulus (GPa) | density (kg/m³) |
|------------------------|-------------------------------|-----------------------------------|----------------------|-----------------|
| 20                     | 38                            | 0.46                              | 211                  | 7850            |
| 100                    | 41                            | 0.5                               | 206                  | —               |
| 200                    | 42                            | 0.5                               | 200                  | —               |
| 300                    | 41                            | 0.54                              | 192                  | —               |
| 400                    | 39                            | 0.54                              | 184                  | —               |
| 500                    | 38                            | 0.63                              | 175                  | —               |

3. Stress analysis of steam-water separator in peak-adjusting operation

There are mechanical stresses and thermal stresses in the steam-water separator during start-up and peak-shaving. The alternating stress is the main cause of fatigue damage of metal materials. Therefore, it is necessary to analyze the stress distribution during the startup and peaking process of the steam separator to analyze the life loss. This paper mainly simulates the cold start, warm start, hot start and different peak shaving conditions.

3.1 Cold start stress analysis

Figure 3 shows the thermal stress field distribution of the thermal stress at the maximum moment. It can be seen that the thermal stress at the intersection of the inlet pipe and the inner wall of the cylinder is the largest. This is mainly because the thermal stress gradient here is large and the structure is discontinuous, so that the thermal stress changes drastically, and stress concentration occurs.

The mechanical stress is mainly caused by the working fluid pressure inside the steam-water separator. Therefore, the maximum mechanical stress appears at the end of the start-up period. At this time, the mechanical stress distribution of the steam-water separator is shown in Figure 4. It can be seen...
from the figure that the stress gradients of the three steam-water inlet pipes of the steam-water separator are relatively large, and the upper mechanical stress of the intersecting line between the inner wall of the cylinder and the inner wall of the inlet pipe has a maximum value.

The total stress during the cold start process is the result of the coupling of mechanical and thermal stresses. Figure 5 shows the total stress distribution cloud at the start of 600s and the start of startup. The maximum stress point within 600s before the start of the initial stage is located at node 746 (maximum thermal stress point) on the intersection of the inner wall of the cylinder and the soda inlet tube.

The maximum stress point after 600s in the middle and late stages of the start is located at the node 901 (maximum mechanical stress point) on the intersection line between the inner wall of the cylinder and the soda water introduction tube. Therefore, the maximum stress value of the total stress at the different moments of starting is always on the line connecting the cylinder and the soda water inlet pipe, but the specific position is uncertain.

Figure 7 is a graph showing the relationship between the two maximum stress points (node 746 and node 901) over time during the cold start process. It can be seen from the figure that both curves are reduced first and then gradually increased. This is because in the initial stage of startup, the internal pressure of the working medium is small, the mechanical stress is small, and the temperature change rate is relatively large, resulting in a relatively large thermal stress.

The total stress mainly depends on the thermal stress and the total stress value reaches the secondary peak at this time. In the middle of the start-up, the thermal stress is small, and the total stress mainly depends on the mechanical stress, so the total stress remains basically unchanged.

During the late stage of the lifting process, the mechanical stress increases with the increase of the working medium pressure, and the thermal stress increases due to the increase of the working temperature. However, the thermal stress is less than the mechanical stress, and the total stress mainly depends on the mechanical pressure. At the end of the start-up, as the boiler full-load working fluid pressure reaches a maximum, the thermal stress tends to zero, the mechanical stress reaches a maximum,
and the total stress of the steam-water separator also reaches a maximum.

Figure 7. Total stress changes at nodes 746 and 901 under cold start

Since the node 901 is numerically larger, this point is taken as the maximum stress point, and the value of the point is taken for calculation in the life analysis.

3.2 Warm start stress analysis

Figure 8 shows the stress distribution cloud diagram when the total stress is maximum. The maximum stress value during the warm state startup is always located in the intersection line between the inner wall of the cylinder and the soda water introduction tube. This is different from the cold start, where the position of the maximum point of total stress during the cold start is uncertain. During warm start, the maximum total stress occurs at the end of the start, when the mechanical stress reaches a maximum.

Figure 8. Total stress distribution cloud map under warm start

Figure 9. Regularity of total stress change under warm start

3.3 Hot start stress analysis

It can be seen from Figure 10 that the dangerous point position of the total stress in the hot start process is consistent with the warm start. At the beginning of the hot start, the total stress changes are relatively flat. This is because the initial thermal stress value is much smaller than the total stress value. The total stress is mainly determined by the mechanical stress value. Therefore, the change in the total pressure is relatively flat. In the middle and late stages of the start-up, the change of the total pressure is consistent with the warm start and the cold start.
3.4 Deep peaking stress analysis

When the grid is at a low point, the deep peak-shaving operation prevents the unit from starting and stopping frequently. During the start-stop process, the pressure-bearing equipment needs to withstand severe temperature changes and pressure changes.

In order to compare and analyze the influence of different peak shaving depths on the life of the steam separator, in the text, we select three variations from 234MW-670MW, 268MW-670MW and 302-670MW, and the stress during the low load peaking operation is calculated separately.

| Operating condition | Cold start | warm start | hot start | Low load operation peak shaving (peaking depth) |
|---------------------|-----------|------------|----------|-----------------------------------------------|
| Maximum stress (MPa) | 366       | 366        | 366      | 362                                           |
| Minimum stress (MPa) | 3         | 55         | 94       | 121                                           |
| Stress amplitude (MPa) | 363     | 311        | 272      | 241                                           |

It can be seen from Table 3 that during the process of peak load regulation at low load, the difference
in stress amplitude is small, and the stress amplitude during peak regulation is smaller than the stress amplitude during startup.

The larger the peaking amplitude, the larger the generated stress amplitude. At the end of the peak load peaking operation, the maximum stress value is the same. The peaking depth is larger, the smaller the minimum stress, the larger the stress amplitude. In various starting modes, the order of stress amplitude from large to small is: cold start, warm start, hot start.

4. Analysis of the effect of peak regulation on life

![American ASME fatigue design curve](image)

In this paper, the US ASME standard is used for life evaluation. For the steam-water separator, the maximum total stress value and the minimum total stress value of the steam-water separator under different working conditions can be obtained by numerical simulation. The difference between the two is the cyclic stress amplitude.

\[
\sigma_{a_{ij}} = \frac{1}{2} \Delta \sigma_{a_{ij},\max} = \frac{1}{2} \left( \sigma_{a_{ij},\max} - \sigma_{a_{ij},\min} \right) \tag{4-1}
\]

\( \sigma_{a_{ij},\max} \) — Main stress maximum,
\( \sigma_{a_{ij},\min} \) — Main stress minimum,
\( \sigma_{a_{ij}} \) — Maximum cyclic stress amplitude,
\( \Delta \sigma_{a_{ij},\max} \) — Maximum cyclic stress amplitude fluctuation range;

After calculating the maximum cyclic stress amplitude \( \sigma_{a_{ij}} \), it is necessary to modify the elastic modulus to convert it into the corresponding cyclic stress amplitude \( \sigma_a \) in the fatigue design curve, then we can obtain the allowable number of cycles \( N \).

\[
\sigma_a = \frac{E_a}{E} \sigma_{a_{ij}} \tag{4-2}
\]

\( E_a \) — Elastic Modulus \( E_a = 2.068 \times 10^5 \text{ MPa} \),
\( E \) — Elastic modulus of the material of the life assessment component;

In this paper, the finite element analysis is used to calculate the stress values during the different starting modes and peaking depth of the once-through boiler. The ASME fatigue life curve is then used to evaluate the life of different operating conditions.
### Table 4. Different working conditions life loss of Steam water separator

| Different operating conditions | Cold start and stop | Warm start and stop | Hot start and stop | Peak shaving depth 65% | Peak shaving depth 60% | Peak shaving depth 55% |
|--------------------------------|---------------------|---------------------|--------------------|-----------------------|-----------------------|-----------------------|
| Stress amplitude               | 363                 | 311                 | 272                | 241                   | 222                   | 222                   |
| Corrected stress amplitude     | 383.6               | 314.2               | 294.9              | 292.3                 | 220.76                | 219.68                |
| Allowed cycle times            | 1.1×10^3            | 3.4×10^3            | 5×10^3             | 4.95×10^3             | 5.8×10^3              | 5.8×10^3              |
| One cycle life loss            | 0.91                | 0.28                | 0.2                | 0.2                   | 0.17                  | 0.17                  |

It can be seen from the above table that in various start-stop modes, the steam-water separator has the smallest stress amplitude during the hot start-stop process, and the hot-state start-stop mode has the smallest life loss for the steam-water separator. Under low load operation peaking mode, the stress amplitude at peaking depth of 65% is bigger than the thermal stress during hot start process, the stress amplitude at the peaking depth of 60% and 55% is smaller than the thermal stress during the hot start process.

5. Conclusions

For 670MW once-through boiler, when the peaking depth is lower than 65%, it is recommended to select the low-load operation mode for peak shaving; when the peaking depth of the boiler is greater than or equal to 65%, it is recommended to use the two-shift mechanism to adjust the peak.

When the peaking depth is lower than 65%, the life damage of the steam separator is less than the restart after the peak load of the low load operation. It is recommended to use the low load operation for peak shaving. In the actual peaking operation process, the crew needs frequent start and stop when using the two-shift mechanism for peak shaving, which is difficult to operate and has a large workload.

At the same time, the boiler needs to be ignited and fired when starting the boiler, and the investment cost is high. Therefore, when the peaking depth is higher than or equal to 65%, the low-load operation mode can be selected for peak shaving, or the two-shift mechanism can be selected for peak shaving.

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