Numerical research on thermal stress of steam cooler tube sheet mechanical structure

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Abstract. Steam cooler is one of the most important mechanical equipment in thermal power generation system and nuclear power generation system. The steam cooler bears a huge temperature gradient load when the working conditions are switched. In order to analyze the thermal stress of steam cooler tube sheet with high temperature load under harsh working conditions, the thermal-structural coupling analysis model of steam cooler tube sheet is constructed with finite element method. The results show that the stress concentration exists at the position connection between heat exchanger tube and cylinder. The maximum stress is located at the outermost heat exchanger tube with the peak stress of 320MPa. The heat exchanger tube layout alone cause higher stress. This situation should be avoided in the design of heat exchanger tube sheet. Furthermore, the strength and safety of the steam cooler tube sheet are evaluated with the stress linearization method. The steam cooler tube sheet design meets the safety requirements of structural strength under high temperature load.

1. Introduction

Shell-and-tube heat exchangers are widely used in modern industry and scientific research work. Steam coolers are typical shell-and-tube heat exchangers, which are mainly composed of headers, shells, tube sheets, heat exchange tubes and other parts [1-3]. The shell side of the steam cooler is quickly filled with high-temperature and high-pressure steam when the working conditions are switched. This will cause the temperature difference and pressure difference between the two ends of the tube sheet to change drastically, which will cause huge thermal deformation and thermal stress in the tube sheet structure. In order to ensure the safety and service life of the steam cooler, it is necessary to carry out stress analysis and evaluation on the tube sheet structure of the steam cooler.

The simplified analysis methods in the current relevant standards and specifications can evaluate the safety of the tube sheet structure at a macro level, but it is difficult to reflect the stress distribution and change law of the tube sheet structure under the combined action of the tube side pressure, the shell side pressure and the temperature load. Yang X.R. analyzed the stress field distribution of the U-tube heat exchanger by finite element method and completed the stress safety assessment [4]. Liu J.Y. studied the thermal stress in the U-shaped heat exchanger tube sheet by finite element method. The results show that the reduction of the thickness of the tube sheet can reduce the peak thermal stress [5]. In summary, the predecessors have conducted stress analysis and evaluation on the uniform temperature field of the heat exchanger tube sheet loaded, and reduced the peak stress by changing the
thickness of the tube sheet. But they did not point out the additional cost of reducing the peak thermal stress.

In this paper, the thermal-structure coupling method is applied to construct an accurate three-dimensional finite element numerical model of the tube sheet structure of the steam cooler. The thermal stress analysis and evaluation of the tube sheet structure under the extreme temperature load under severe working conditions are carried out.

2. Thermal-structure multi-field coupling analysis process of tube sheet
When the tube sheet structure is subjected to the temperature load of the working fluid on both sides of the cold and heat, the expansion degree of each part of the structure is not consistent. As a result, thermal stress is generated. Therefore, the thermal stress of the tube-sheet structure comes from the interaction between the two physical fields of heat and stress, which is a typical multi-field coupling problem. Based on the ANSYS APDL tool, the thermal-mechanical coupling numerical analysis of the tube sheet structure is conducted by one-way coupling method in this paper. The specific analysis process is shown in Figure 1.

3. Meshing
The heat exchanger tube bundle is arranged in a regular triangle. The main geometric dimensions are shown in Table 1. The shell and the heat exchange tube are divided by hexahedral units. The tube sheet structure is divided by tetrahedral elements. After verification of grid independence, it is determined that the number of nodes in the final grid model is 160,000 and the number of elements is 150,000.
4. Thermal analysis of tube sheet structure

The heat exchanger material can be regarded as isotropic. The material performance parameters are shown in Table 2. Based on the tube side and shell side temperature and the convective heat transfer coefficient measured by the steam cooler heat exchange experiment listed in Table 3, the corresponding boundary conditions are applied to the model.

| Number | Variable | Unit   | Value   |
|--------|----------|--------|---------|
| 1      | Material type | —      | 304     |
| 2      | Density   | kg/m³  | 7930    |
| 3      | Elastic Modulus | GPa  | 200     |
| 4      | Poisson’s ratio | —      | 0.3     |
| 5      | Linear expansion coefficient | °C⁻¹ | 17.2×10⁻⁶ |
| 6      | Thermal Conductivity | W/(m·°C) | 16.3 |
| 7      | Yield Strength | MPa    | 310     |

Table 3. Temperature and heat transfer coefficient of steam cooler.

| Number | Variable | Unit           | Value |
|--------|----------|----------------|-------|
| 1      | Inner temperature at tube passage | °C   | 18     |
| 2      | Outlet temperature at tube passage | °C  | 38     |
| 3      | Inlet temperature at the shell passage | °C | 176 |
| 4      | Outlet temperature at the shell passage | °C | 40     |
| 5      | Pressure of tube passage       | MPa  | 0.1    |
| 6      | Pressure of shell passage      | MPa  | 0.8    |
| 7      | Heat transfer coefficient of tube passage | W/(m²·°C) | 3304 |
| 8      | Heat transfer coefficient of shell passage | W/(m²·°C) | 10000 |
As shown in Figure 3, the temperature field distribution of the tube sheet structure is obtained by thermal analysis. The temperature in the tube sheet decreases with distance from the contact surface of the high-temperature steam zone with the tube sheet. The convective heat transfer coefficient of high-temperature steam is higher than that of water. The temperature gradually decreases from 170°C on the high-temperature steam side to 18°C on the cold water side. Therefore, the temperature field distribution of the tube sheet is that the temperature of the high-temperature steam zone decreases outward to the cold water temperature with an annular gradient.

It can be further seen from the figure that the temperature of the tube sheet increases from 36°C to about 175°C along the thickness direction, which is close to the temperature of the high-temperature steam in the shell side. In the non-piped area, the temperature in the thin layer area on the shell side tube sheet surface is the highest and the temperature in the thin layer area on the tube side tube sheet surface is the lowest. This is a typical skin effect. The temperature in the non-piped area changes linearly and the temperature gradient is relatively small. The temperature in the piped area changes nonlinearly and the temperature gradient is relatively large. The right side of Figure 3 shows the temperature distribution in the upper half of the tube sheet. It can be seen that the temperature gradient of the relatively independent heat exchange tube in the lower right corner is obviously larger than that of the other heat exchange tubes.

5. Thermal analysis of tube sheet structure

The temperature field distribution of the tube sheet structure is obtained by thermal analysis. On this basis, the thermal element is converted into the structural element. The temperature field calculation results obtained from the thermal analysis are imported and loaded into the tube sheet model as a body load. Moreover, the working fluid pressure on the shell side and the tube side is applied as a surface load to the corresponding surfaces of the shell, the heat exchange tube and the tube sheet. Finally, the structural stress analysis of the tube sheet model is carried out.

Figure 4 shows the variation characteristics of stress at the interface between the upper and lower part of the tube sheet along the thickness of the tube sheet, where $P_L$ represents the primary local film stress, $P_b$ represents the primary bending stress, and $Q$ represents the secondary stress. The interface between the upper and lower part of the tube sheet is the interface between steam and single-phase water. The corresponding maximum thermal stress is 202MPa, which occurs at the junction of the tube sheet and the heat exchanger shell. It is mainly due to the discontinuity of the structure between the heat exchanger shell and the tube sheet, which causes the uncoordinated expansion and contraction under operating conditions to form a local stress concentration.

It can be further seen from Figure 4 that the maximum stress of the heat exchanger tube sheet appears at the extreme edge of the piped area. The peak stress is about 320MPa. The heat exchange tubes in the edge area are arranged independently. Therefore, a large temperature gradient will be generated, which will cause large thermal deformation and thermal stress.
In order to obtain the distribution law of force and other required parameters intuitively, different dangerous sections can be selected by observing the stress distribution cloud diagram of the structure. Furthermore, the path containing the maximum stress point on the dangerous section is selected and the stress is identified and classified along this path. Thus, the stress distribution law and evaluation input are obtained. As shown in Figure 5, three paths along the thickness direction are defined on the tube sheet. The A path is located in the tube sheet layout area. Path B is located at the junction of the cylinder and the tube sheet. Path C is located in an independent area where the heat exchange tubes are arranged. All paths of the tube sheet are from the tube side surface to the shell side surface and along the normal direction of the tube sheet surface.

Figure 5. Definition of tube sheet stress analysis path.

According to relevant standards, there are 3 assessment criteria for the strength check of tube sheet structure. $P_L$ is not more than 1.5 times the allowable stress. $P_L + P_b$ is not more than 1.5 times the allowable stress. $P_L + P_b + Q$ is not more than 3 times the allowable stress. The allowable stress is the

Figure 6. Stress distribution of each path on the tube sheet.
yield limit of the material divided by the safety factor. The safety factor is set to 2. As a result, the allowable stress value is 155MPa.

Table 4. Result of stress safety assessment of tube sheet structure

| Path | P/L/MPa | P/L+P/b/MPa | P/L+P/b+Q/MPa | Result |
|------|---------|-------------|---------------|--------|
| A    | 41.09   | 52.36       | 250.45        | Safe   |
| B    | 47.09   | 112.87      | 186.8         | Safe   |
| C    | 78.08   | 121.93      | 281.76        | Safe   |

As shown in Table 4, the linearized stress evaluation of the heat exchanger tube sheet has been conducted. Although there are large thermal stresses at the junction of the tube sheet, the heat exchange tube and the cylinder. However, the tube sheet structure still meets the strength safety requirements.

6. Conclusions

The steam cooler is an important heat exchange device in the power generation system. In order to ensure the safety of the steam cooler, it is necessary to carry out stress analysis and evaluation on the tube sheet structure of the steam cooler. In this paper, a one-way coupling method is applied to conduct a thermal-structural multi-physics coupling numerical analysis of the steam cooler tube sheet structure. The main conclusions are as follows:

(1) The temperature and pressure on the shell side of the heat exchanger will rise sharply when the working conditions are switched. The internal temperature field of the tube sheet structure changes greatly. As a result, a significant temperature gradient load is caused and the structure generates large thermal stress.

(2) The maximum stress of the heat exchanger tube sheet appears at the extreme edge of the heat exchange tube arrangement area. The peak stress value is about 320MPa. The design of heat exchanger should try to avoid independent arrangement of heat exchange tubes. In this way, the local temperature gradient can be reduced and the stress concentration phenomenon can be suppressed. The strength safety of the tube sheet structure can be increased.

(3) The stress linearization method is used to evaluate the strength safety of the dangerous part of the tube sheet structure. The results show that the steam cooler tube sheet structure meets the strength safety requirements when the working conditions are switched.

The three-dimensional finite element numerical method and the stress linearization evaluation method are combined to realize the thermal stress analysis and evaluation of the steam cooler tube sheet structure. It provides an important technical foundation for supporting the development and design of core heat exchange equipment for advanced power generation systems in the future.

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