Study on structure strength design of large square opening of jacketed equipment

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Abstract. Due to the requirement of process, a large square opening is set through the wall thickness of shell and jacket of a jacketed equipment, for which this equipment does not meet the design requirement of “design by rules”. In this paper, the geometric model of this jacketed equipment with large square opening is established, and then the finite element mesh model is obtained by the method of sweep. Based on this, a corresponding load is imposed on the inner and outer wall of the shell, the inner wall of the jacket, the inner wall of the square box flange, and the bolt section of the square box flange. And a fixed constraint is imposed on the cross section of the shell and jacket. Then the stress distribution is obtained by the analysis and calculation of the model. In the high stress areas, stress linearization method is used to check the strength. Different paths are set along the thickness direction of the shell, jacket, square box plate, etc. According to analysis of the results above, it is found that the large square opening structure of jacketed equipment satisfies the strength requirements under the calculated conditions, and the most dangerous area is the joint of square box and square box flange or the joint of shell and nozzle.

1. Introduction
With the continuous development of engineering technology in petrochemical industry, the opening on pressure vessel is becoming more and more complex. And it is often necessary to set large openings on vessels. These larger openings will weaken the strength of the vessel to a large extent, and a complex stress state will be formed at the edge of the opening [1]. There are two main design methods for pressure vessels, one is “design by rules” (such as GB150 [2]), its design criterion is elastic failure; the other is “design by analysis” (such as JB4732 [3]), it is based on stress analysis. Compared with the two methods, the latter has the advantages of greatly improving the design accuracy, innovating the elastic stress assessment method, etc. [4]. When the opening on pressure vessel exceeds a certain range, it will not meet the requirement of “design by rules”. At this time, it is a good choice to use the finite element analysis design method, which could truly reflect the stress distribution of various parts of the structure, so it can be used in the reinforcement calculation of various large openings [5].

In this paper, for a jacket equipment with large square opening, the finite element model is established, and the stress intensity distribution contour is obtained. By using the stress linearization method, different paths are set along the thickness direction of the shell, jacket and square box plate to check the strength.
2. Geometric model
The jacket equipment has a total length of 4000 mm, a height of about 3800 mm, an outer diameter of about 1300 mm, and its wall thickness is 22 mm. And the jacket has an outer diameter of about 1380 mm, wall thickness of 10 mm. The maximum size of the inner square box is about 1400×1150 mm, and the maximum size of the outer square box is about 1500×1300 mm. The boundary size of the square box plate is about 1700×450 mm, and there are 48 bolt holes with a diameter of 36 mm on the square box plate. As shown in Figure 1.

The model is reasonably simplified during the modeling, and the design modeler module in ANSYS Workbench is used. The shell, jacket, square box, square box flange, vacuum nozzle, vacuum nozzle seat, measuring nozzle and measuring nozzle flange are established, as shown in Figure 1. The material of shell and square box is Q345R, and its relevant material parameters are listed in Table 1.

Table 1. Material properties of Q345R

| Material | Design temperature (°C) | Plate thickness (mm) | Intensity index at room temperature | Allowable stress (MPa) |
|----------|------------------------|----------------------|------------------------------------|-----------------------|
|          |                        |                      | $R_m$ (MPa) | $R_{el}$ (MPa) |                  |
| Q345R    | 100                    |                      | 510       | 345         | 196                |
|          | >6~16                  |                      | 490       | 325         | 188                |
|          | >16~25                 |                      | 490       | 325         | 188                |
|          | >25~36                 |                      | 470       | 305         | 181                |

3. Finite element model
3.1. Meshing model
The whole model is reasonably divided by the operation of “Slice”. In order to ensure the subsequent meshing and the quality of the mesh, regular bodies are divided as much as possible, the divided bodies of the whole model are shown in Figure 2.

The quality of the mesh has a great influence on the results of further analysis and calculation, thus the quality should be well ensured. Sweep method is used for meshing. The mesh size is adjusted by defining the number of meshes on each edge of the body. For irregular bodies, regular hexahedral meshes are generated as much as possible by controlling the number of volume meshes. After several times of adjustment, the final number of nodes is about 1150000, and the number of elements is about 235000. The mesh quality is evaluated from eight aspects: element quality, mesh aspect ratio, Jacobian ratio, distortion coefficient, parallel deviation, maximum wall angle, divergence and orthogonal quality, and the results show that the current mesh quality is good. The whole mesh model is shown in Figure 3 (a), and Figure 3 (b) and Figure 3 (c) are local mesh models of large square box and vacuum nozzle, respectively.

Figure 1. Geometric model
Figure 2. Divided bodies of the whole model

(a) whole model  (b) large square box  (c) vacuum nozzle

Figure 3. The meshing model

3.2. Loading and boundary conditions
The process conditions are listed in the Table 2. Because the pressure and temperature under the design condition are greater than that under the working condition, only the design condition is considered in the analysis.

Table 2. Process conditions

|                  | Shell | Jacket |
|------------------|-------|--------|
| Working pressure /MPa | 0.19  | 0.095  |
| Design pressure /MPa | 0.2   | 0.1    |
| Working temperature /°C | 80    | 20     |
| Design temperature /°C | 100   | 20     |
| Working medium     | N₂    | H₂O    |
| Corrosion allowance /mm | 2     | 2      |
| Service life /year | 10    | 10     |
4.  Strength results analysis and discussion

The stress distribution contour of the jacketed equipment under the design condition is shown in Figure 5. It can be seen that the maximum stress of the equipment occurs at the joint of the square box. In addition, the joint of the shell and the nozzle also belongs to the high stress area.

In order to use the stress linearization method to check the stress, check paths should be set. For the convenience of indicating the position of the path, four intersections of the upper square box and the jacket is numbered in clockwise, as shown in Figure 6. The number of the other four intersections of the lower square box corresponds to the number of the upper square box. When setting the path, the point with the maximum stress is taken as the starting point, and the path goes along the wall thickness direction. As the stress of the lower square box is larger than that of the upper square box, only the path analysis on the lower square box is conducted for the consideration of the most dangerous situation. Taking the maximum stress points of four intersection points of lower square box as the starting point, 20 paths are set in the wall thickness direction of square box plate 1, square box plate 2 and jacket. Figure 7 shows the schematic diagram of path 1-6. In the analysis of square box flange, 6 paths are set along the wall thickness of square box flange, the wall thickness of outer square box plate and inner square box plate. In the analysis of vacuum nozzle, the highest and lowest points of the inner and outer nozzle are selected as the starting points, 8 paths are set along the wall thickness of the vacuum nozzle and jacket.

The strength check results of the lower square box are listed in Table 3. The results of stress linearization for all paths with higher stress set on the lower square box are less than the allowable limit, and all the check results are satisfied. The local membrane stress of path 1 and path 6, and the primary plus secondary stress of path 1, path 3, path 5 and path 6 are larger. According to the schematic diagram of the path, it can be seen that path 1 locates at position 2, and starts from the joint of the outer plate of the square box and the outer wall of the jacket, and it goes along the wall thickness direction of the outer plate of the square box. Path 3 locates at position 1, and starts from the joint of the outer plate of the square box and the inner wall of the jacket, and it goes along the wall thickness direction of the jacket. Path 5 locates at position 3, and starts from the joint of the outer plate of the square box and the inner
wall of the jacket, and it goes along the wall thickness direction of the jacket. Path 6 locates at position 4, and starts from the joint of the outer plate of the square box and the inner wall of the jacket, and it goes along the wall thickness direction of the jacket. These positions are dangerous area, which should be focused on. In addition, it is also found that the maximum stress occurs at the joint of the square box and jacket.

**Figure 5.** Stress distribution contour

**Figure 6.** Schematic diagram of the path position

**Figure 7.** Schematic diagram of path 1-6
Table 3. Strength check results of the lower square box

| Path  | Calculated value | $S_{II} (P_L)$ Allowable limit 1.5$K_S_m$ | Calculated value | $S_{IV} (P_L+P_b+Q)$ Allowable limit 3$S_m$ | Check results |
|-------|------------------|------------------------------------------|------------------|------------------------------------------|---------------|
| Path 1 | 229.48           | 294                                      | 464.51           | 588                                      | Satisfy       |
| Path 2 | 183.20           | 294                                      | 234.01           | 588                                      | Satisfy       |
| Path 3 | 181.83           | 294                                      | 361.46           | 588                                      | Satisfy       |
| Path 4 | 138.21           | 294                                      | 182.44           | 588                                      | Satisfy       |
| Path 5 | 181.83           | 294                                      | 361.46           | 588                                      | Satisfy       |
| Path 6 | 201.78           | 294                                      | 374.17           | 588                                      | Satisfy       |
| Path 7 | 65.76            | 294                                      | 118.92           | 588                                      | Satisfy       |
| Path 8 | 161.33           | 294                                      | 204.89           | 588                                      | Satisfy       |
| Path 9 | 63.37            | 282                                      | 148.58           | 564                                      | Satisfy       |
| Path 10| 186.63           | 282                                      | 91.60            | 564                                      | Satisfy       |
| Path 11| 47.15            | 282                                      | 75.69            | 564                                      | Satisfy       |
| Path 12| 86.26            | 282                                      | 175.92           | 564                                      | Satisfy       |
| Path 13| 61.50            | 282                                      | 88.81            | 564                                      | Satisfy       |
| Path 14| 93.48            | 282                                      | 108.61           | 564                                      | Satisfy       |
| Path 15| 88.34            | 282                                      | 172.45           | 564                                      | Satisfy       |
| Path 16| 107.42           | 282                                      | 131.68           | 564                                      | Satisfy       |
| Path 17| 89.50            | 282                                      | 114.12           | 564                                      | Satisfy       |
| Path 18| 26.81            | 282                                      | 46.32            | 564                                      | Satisfy       |
| Path 19| 58.28            | 282                                      | 64.59            | 564                                      | Satisfy       |
| Path 20| 69.68            | 282                                      | 69.68            | 564                                      | Satisfy       |

The strength check results of the lower square box flange are listed in Table 4. The results of stress linearization for all paths with higher stress set on the lower square box flange are less than the allowable limit, and all the check results are satisfied.

Table 4. Strength check results of the lower square box flange

| Path  | Calculated value | $S_{II} (P_L)$ Allowable limit 1.5$K_S_m$ | Calculated value | $S_{IV} (P_L+P_b+Q)$ Allowable limit 3$S_m$ | Check results |
|-------|------------------|------------------------------------------|------------------|------------------------------------------|---------------|
| Path 21| 15.09            | 259.5                                    | 40.98            | 564                                      | Satisfy       |
| Path 22| 40.61            | 294                                      | 61.20            | 588                                      | Satisfy       |
| Path 23| 75.65            | 294                                      | 95.78            | 588                                      | Satisfy       |
| Path 24| 16.74            | 259.5                                    | 64.37            | 564                                      | Satisfy       |
| Path 25| 59.55            | 282                                      | 70.28            | 564                                      | Satisfy       |
| Path 26| 53.66            | 282                                      | 70.13            | 564                                      | Satisfy       |

Table 5. Strength check results of the vacuum nozzle

| Path  | Calculated value | $S_{II} (P_L)$ Allowable limit 1.5$K_S_m$ | Calculated value | $S_{IV} (P_L+P_b+Q)$ Allowable limit 3$S_m$ | Check results |
|-------|------------------|------------------------------------------|------------------|------------------------------------------|---------------|
| Path 27| 13.64            | 294                                      | 23.35            | 588                                      | Satisfy       |
| Path 28| 24.80            | 294                                      | 27.49            | 588                                      | Satisfy       |
| Path 29| 14.78            | 282                                      | 41.03            | 564                                      | Satisfy       |
| Path 30| 26.60            | 294                                      | 30.84            | 588                                      | Satisfy       |
| Path 31| 17.59            | 294                                      | 26.95            | 588                                      | Satisfy       |
| Path 32| 18.92            | 294                                      | 28.96            | 588                                      | Satisfy       |
| Path 33| 29.10            | 282                                      | 34.13            | 564                                      | Satisfy       |
| Path 34| 14.68            | 294                                      | 27.93            | 588                                      | Satisfy       |
The strength check results of the vacuum nozzle are listed in Table 5. The results of stress linearization for all paths with higher stress set on the vacuum nozzle are less than the allowable limit, and all the check results are satisfied.

5. Conclusion
(1) The finite element model of a jacketed equipment with large square openings is established, the loading is applied according to the design conditions (jacket pressure, design pressure and bolt load, etc.), and the stress intensity distribution contour is obtained. The stress linearization method is used to check the strength, and the results show that the equipment meets the strength requirements under the design conditions.

(2) By analyzing the stress contour of the jacketed equipment and combining with the stress linearization results, it is found that the areas with high stress occurs at the joint of square box and square box flange or the joint of shell and nozzle, these are the areas where cracking is most likely to occur for the jacketed equipment.

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