Research on Load Checking of In-service Pressure Vessel Nozzle

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Abstract. Pressure vessel is an important part of industrial production. Pressure vessels usually have many nozzles, which are connected to other devices through pipeline. Due to the large thermal stress caused by the thermal expansion of the pipeline, the load on the nozzle of the connected vessel will be increased. When the load on the nozzle is too large, it may cause local deformation of the vessel, or even cause cracking at the root of the nozzle. Increasing the flexibility of the pipeline can reduce the load on the nozzle. Taking the flare system of the factory as an assessment case, this paper introduced a new load checking method. The software was used to simulate the load on the liquid separation tank connected with the flare gas pipeline. The calculated load of the liquid separation tank nozzle met the technical conditions of the manufacturer.

1. Introduction
Due to the high temperature, the pipeline will cause greater thermal stress after being heated, which will increase the load on the nozzle of connected pressure vessels. Excessive load on the nozzle of the vessel may cause local deformation or even cracking at the nozzle. Therefore, it is significant to analyse and calculate the load of the nozzle. The pipeline is very important to the load of the vessel nozzle, the pipeline system and the vessel must be simulated at the same time. Load calculation of vessel nozzle, which generally includes force and torque. The risk of vessel can be evaluated through calculation to ensure safe operation of vessel.

2. Nozzle load checking theory

2.1 Nozzle load source and calculation
When the pipeline changed from the cold state to hot state, the force and torque of the pipeline on the nozzle will be caused by the thermal expansion. As shown in Figure 1 below, B was simulated as the vessel nozzle. When A was fixed, B expanded axially to B’ due to the rising temperature. The expansion length, $\Delta t$, can be calculated by Eq. (1). If the pipeline was free to expand, there will be no thermal stress. On the contrary, when B was also fixed, there will be a huge thermal stress, $\sigma$, calculated by Eq. (2).

$$\Delta t = L \cdot \alpha \cdot \Delta T$$  \hspace{1cm} (1)
\[ \sigma = E \cdot \alpha \cdot \Delta T \]  

Here, \( E \) is elasticity modulus, \( \alpha \) is coefficient of thermal expansion, \( L \) is pipeline length, \( m \), \( \Delta T \) is temperature difference, \( K \), and \( \alpha \) is coefficient of thermal expansion, \( 1/K \).

**2.2 Method of reducing nozzle load**

If the pipeline direction from point A to point B was changed into Figure 2, the thermal stress at point B was less than that in FIG. 1 under the same other conditions. The layout of pipeline system provided inherent flexibility through changing direction with large deformation capacity. According to the above analysis, it can be found that the flexibility of the pipeline can effectively reduce the load of vessel nozzle. The flexibility of the pipeline reflected the degree to absorb heat and other displacements by deforming itself [1].

In ASME B31.3-2016, a total of six basic and special requirements need to be met for pipeline flexibility [2]. There are two main methods to increase the flexibility of the flare gas pipeline. The first is to change the direction of the pipeline to increase its flexibility as mentioned above. The second is to add the expansion joint, spring support hanger or other vessel permitting angular, rotational, or axial movement. The second method is considered only when the field is limited also the compensation amount is large, otherwise, the first method should be adopted. The high cost and short life of compensators are also important factors.

**2.3 Nozzle load check standards**

The load caused by the pipeline on the vessel shall not exceed the allowable value specified by the manufacturer or the standards [3]. When the nozzle load of the vessel exceeds the manufacturer or the standard value, Welding Research Council (WRC) Bulletin 107 or WRC Bulletin 297 will be further used to check the local stress of the joint between the nozzle and the shell to determine whether the allowable stresses are exceeded. WRC Bulletin 107 and WRC Bulletin 297 are two important design guidelines for pressure vessel design, which has been widely used in the analysis design. Local stresses can be used to analyse the stresses in cylindrical or spherical vessels in WRC Bulletin 107. WRC Bulletin 297 is a supplement to WRC Bulletin 107 and is specifically applicable to cylindrical nozzles in cylindrical vessels. It should be mentioned that there are many restrictions when using WRC [4, 5]. The nozzle load does not exceed the manufacturer's requirements, the nozzle can be considered safe and the stress analysis of the vessel nozzle can be cancelled.

Because the stresses computed by WRC 107 are highly localized, they don’t fall immediately under the ASME B31 code rules. However, Appendix 4-1 of ASME Section VIII, Division 2 “Mandatory Design Based on Stress Analysis” does provide a detailed approach for dealing with these local stresses [6]. Check standards for piping and pressure vessels nozzle can be selected using Table 1.

| No. | Type | Standard                      |
|-----|------|-------------------------------|
| 1   | 19   | WRC 107/297                   |
| 2   | 19   | ASME B31 code                 |
| 3   | 19   | Manufacturer/ SH/T 3074-2018   |
3. Assessment case

3.1 Piping system model
The flare gas was collected to the pipeline from The desulfurization device (node 10) to the liquid separation tank (T-301), which were placed overhead on the pipeline gallery. The connecting flange (Node 150) at the end of the pipeline was connected with the inlet nozzle flange (Node 3230) of the liquid separation tank through fasteners. CAESAR II software is professional pipeline stress analysis software developed by INTERGRAPH Corporation based on beam element model of finite element analysis, which has been widely used in petroleum, chemical, electricity and other fields. The pipeline material was 20# carbon steel. The basic parameters of the flare gas pipeline were shown in Table 2.

| Parameter                      | Value         |
|--------------------------------|---------------|
| Operating Pressure (P1)        | 0.15Mpa       |
| Design Pressure (P2)           | 0.35Mpa       |
| Operating Temperature (T1)     | 180°C         |
| Design Temperature (T2)        | 220°C         |
| Specifications (main)          | Φ530×9.0mm     |
| Insulation Thickness           | 70mm          |

After entering the data according to TABLE 2, we need to set the restraints, which contained three types of supports (see Figure 3) in the pipeline system. Anchors limited the linear displacement in X, Y, and Z directions and the angular displacement in the three directions on node 80 and 100. Sliding Supports resisted the forces due to the weight of the pipeline and steam. So, they limited the linear displacement in –Y direction (opposite directions in the coordinate system). In order to prevent the impact of radial displacement on the surrounding pipeline expansion, such as collision and extrusion. Guides only allowed axial expansion and a short radial displacement (3~5mm) on node 40 and 70.

3.2 Liquid separation tank model
The structure of the liquid separation tank must be simulated to calculate the real load on the fixed support and the sliding support of the liquid separation tank. The basic parameters of the liquid separator were shown in Table 3.

| Parameter                  | Value         |
|----------------------------|---------------|
| Design Pressure (P2)       | 0.40 Mpa      |
| Design Temperature (T2)    | 250°C         |
| Fixed Saddle Node          | 3010          |
| Sliding saddle Node        | 3410          |
| Inlet Flange Node          | 3230          |
| Material                   | Q345R         |
| Volume                     | 12.5 m³       |
| Cylinder Diameter          | 1600mm        |
| Thickness                  | 12mm          |
The liquid separator was a horizontal cylindrical pressure vessel supported by double saddles. The cylinder of the liquid separator was simulated by the pipeline from node 3100 to 3500 (see Figure 4). The saddle near the inlet nozzle was fixed and the other end was the sliding saddle. The fixed saddle (node 3010) limited all displacement in X, Y and Z directions on node 3010. The sliding saddle (node 3410) resisted the forces due to the weight of the liquid separator on node 3400. The nodes 3400 and 3410 were connected by a weightless rigid piece that simulated the load between the liquid separation tank and the sliding saddle. The node 3230 and node 3220 simulated the nozzle flange, while node 3220 and node 3210 simulated the pipeline connecting between the nozzle flange and the liquid separator. The nodes 3210 and 3200 were also connected by a weightless rigid, and the distance between them was radius of the cylinder. Nodes 3300 to 3330 were the outlet end similar to the inlet.

The inlet was set as a rigid nozzle, and the load of the node 150 was transferred to the node 3230 through the "CNODE" command. The "Rigid" command was used to simulate a rigid without weight, which can be loaded into the center of the cylinder. The node 140 and 150 simulated the flare gas connected to the nozzle [7]. The 3D model of liquid separation tank was shown in Figure 5.

3.3 Model combination calculation

The stress state of the pipeline system can be calculated by simulating different working conditions. The divided working conditions were shown in Table 4 (W= the pipeline and flare gas weight). It should be noted that T2 and P2 should be selected according to the basic parameters of the liquid separation tank (see Table 3) and the pipeline (see Table 2) respectively.

| Name | Load case | Working condition | Note                  |
|------|-----------|-------------------|-----------------------|
| L3   | W+T2+P2  | Operation         | Nozzle Load Calculation|
| L4   | W+P2     | Sustained Load    | Primary Stress Analysis|
| L6   | L6=L3-L4 | Expansion Load    | Secondary Stress Analysis|

By comparing the nozzle load calculated by the software with the load specified by the manufacturer in Table 5, it can be found that the calculated nozzle load of the liquid separation tank
was less than the allowed data (absolute value) by the manufacturer, so the nozzle load of the liquid separation was safe. The stress analysis of the vessel nozzle can be avoided.

Table 5. The basic parameters of the liquid separator

| Name             | $F_x/N$ | $F_y/N$ | $F_z/N$ | $M_x (N\cdot m)$ | $M_y (N\cdot m)$ | $M_z (N\cdot m)$ |
|------------------|---------|---------|---------|------------------|------------------|------------------|
| Allowed Data     | 11200   | 12750   | 9875    | 19700            | 23600            | 18500            |
| Calculation Data | -9635   | -11392  | 2079    | -9745            | 17912            | 15085            |

4. Conclusions

Under the same conditions, the more flexible the piping, the less thermal stress will generate. The flexibility of the pipeline is related to the geometry of the pipeline, the length of expansion, and the elastic modulus. Priority is given to increasing the flexibility by changing the direction of the pipeline.

The software CAESAR II was used to build the piping system and the liquid separation tank. The load on the connected nozzle of the liquid separation tank was calculated. By modelling and analysing the system in advance, reliable theoretical calculation data was obtained, which met the requirements of the manufacturers. Generally, the allowable load specified by the manufacturer is preferred to the load by standards because its data is more specific to the project. If the nozzle load of the vessel exceeds the manufacturer or the standard value, Research Council (WRC) Bulletin 107 or WRC Bulletin 297 will be further used to check the local stress of the joint between the nozzle and the shell to determine whether the allowable stress is exceeded. It should be noted basic parameters such as temperature, pressure and materials should be distinguished when the vessel and pipeline were simulated.

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