Application of Pipeline System Stress Analysis in Inspection

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Abstract. Industrial pipeline is generally laid overhead along the pipe gallery. When the pipeline changes from cold state to heat state, the pipeline will have thermal expansion, which will generate thermal displacement and thermal stress. As a kind of heat medium, Steam has been widely used in industrial production. The pipeline has been in service at high temperature for a long time, which is prone to metal material degradation such as graphitization and spheroidization. The accidents of steam pipeline occurred frequently in recent years, so we must pay more attention to the safety of steam pipeline. The traditional inspection method adopts a random sampling model which has the risk of over inspection and missing inspection. This paper introduced the stress analysis of a steam pipeline based on ASME B31.3. Through the software, the model of the pipeline was established. According to the calculation results, a targeted inspection scheme was established and the inspection was more economical and effective.

1. Introduction

Thermal pipeline is important in industrial production. The steam is often used in industrial production. According to the degree of saturation, it can be divided into superheated steam and saturated steam. High temperature is easy to cause material creep, internal spheroidization, graphitization and other material deterioration.

The main consequences of steam pipeline explosions are large physical shock waves and high temperature burns. In recent years, steam pipelines occurred frequently, which not only caused considerable economic losses to enterprises, but also infringed on personal safety. On August 11, 2016, a high-pressure steam pipeline exploded in the factory in Hubei province, China, which killed 22 people and injured four. The main reason was that the nozzle installed on the steam pipeline was a poor quality product with serious unqualified quality [1]. The weld defect was extended under the action of high temperature and high pressure, the accident occurred in the local crack. On December 23, 2017, six people were killed and three seriously injured in a steam pipeline accident at the plant in Jiaxing City, Zhejiang Province, China. The reason of accident was that the design required the pipeline material to be 12Cr1MoVG alloy steel, which was actually misused as 20# carbon steel, the mechanical strength and impact toughness of the material didn’t meet the requirements [2]. Periodic Inspection Regulation for Industrial Pressure Piping (TSG D7005-2018) explicitly requires stress analysis and checking in some cases to determine the safety of the pipeline. Through the analysis of the stress condition of the pipeline system, we can evaluate the high risk area with large stress load,
which is helpful for the inspectors to make a targeted inspection program, so it is of great significance for the stress analysis of the thermal pipeline.

2. Experimental apparatus and object Stress analysis discriminant

The stress analysis of pipeline can be divided into dynamic analysis and static analysis [3]. This paper introduced a static analysis method, which mainly included primary stress calculation, secondary stress calculation and pipeline thermal displacement calculation. With the increasing popularity of computer, the detailed stress analysis is mainly realized by computer. Computer analysis of all pipelines is uneconomical and impractical. Design Code for Industrial Metallic Piping (GB50316-2000 The 2008 Edition) explicitly requires flexible calculation to determine the safety of the pipeline, when the design temperature is less than -50℃ or more than 100℃ [4]. CAESAR II software is professional pipeline stress analysis software developed by INTERGRAPH Corporation, which is based on beam element model of finite element analysis and has been widely used in petroleum, chemical, electricity and other fields.

2.1 Primary stress check

The primary stress is in balance with the external load. The basic characteristic of a primary stress is that it is not self-limiting. Primary stresses which considerably exceed the yield strength will result in failure or at least in gross distortion. The Primary stress increases when the distance of supports between elevated pipelines is longer than the allowable span of the pipeline. In general, the smaller value of pipeline span under strength condition, \( L_1 \), calculated by Eq. (1) and pipeline span under stiffness condition, \( L_2 \), calculated by Eq. (2) is considered as the maximum allowable span for continuous laying pipeline. According to ASME B31.3-2016, three conditions need to be met to pass the primary stress check [5]:

a) Stresses due to internal pressure shall be considered safe when the wall thickness of the piping component, including any reinforcement meets the requirements.

b) Stresses due to external pressure shall be considered safe when the wall thickness of the piping component and its means of stiffening meet the requirements.

c) The sum of the longitudinal stresses due to sustained loads, \( S_L \), calculated by Eq. (3) shall not exceed \( S_h \).

\[
L_1 = 0.071 \sqrt{\frac{Z \cdot S_h}{q}} \quad (1)
\]

\[
L_2 = 0.048 \sqrt{\frac{E \cdot \pi \cdot (D_c^2 - D_f^2)}{64q}} \quad (2)
\]

\[
S_L = \left[ \frac{I y E z}{A_p} + \sqrt{\left(I_y M_y\right)^2 + \left(I_x M_x\right)^2} \cdot \frac{Z}{Z} + 4S_e^2 \right]^{0.5} \quad (3)
\]

2.2 Secondary stress check

The secondary stress is caused by the constraint of adjacent parts when the pipeline is expanded by heat. Compared with the primary stress, the basic characteristic of the secondary stress is that it is self-limiting. Local yielding and minor distortions can satisfy the conditions that cause the stress to occur and failure from one application of the stress is not to be expected, so periodic plastic deformation, which may cause fatigue failure should be avoided. According to ASME B31.3-2016, the requirements for passing the secondary stress check is that the computed displacement stress range, \( SE \), calculated by Eq.(4) in a piping system shall not exceed the allowable displacement stress range, \( SA \), calculated by Eq.(5) [5].
2.3 Simplified discriminant

The computational work of pipeline system is so large that it is almost impossible to solve it manually. It is important to use simplified methods to quickly judge the safety status of some pipelines, especially in the field of inspection. ASME B31.3-2016 introduces a simplified discriminant method for secondary stress [5]. If the following three conditions are met, the discriminant can be expressed by Eq. (6). It can be considered that the pipeline is flexible enough when satisfying the discriminant and the secondary stress generated by thermal expansion is within the allowable range. However the result is conservative.

a) The pipeline is of uniform size.

b) The pipeline system has no more than two points of fixation.

c) There are no intermediate restraints.

\[
\frac{D_{xy}}{(L-U)^2} \leq 208.4
\]

3. Inspection case

The steam pipeline was sent from zone A to zone B, C and D in the factory. Self-compensation structure of the steam pipeline was used to reduce the thermal stress. The basic parameters of the steam pipeline were shown in Table 1. The actual layout of pipeline on site was shown in Figure 1. ASME B31.3-2016 was applicable to the stress analysis of overhead steam pipeline in the factory. This was the first regular inspection of the steam pipeline, which has been used since 2015.

Table 1. The parameters of the steam pipeline

| Parameter | Value          |
|-----------|----------------|
| Operating Pressure (P1) | 0.8 MPa |
| Design Pressure (P2)     | 1.1 MPa  |
| Operating Temperature (T1) | 175°C |
| Design Temperature (T2)  | 190°C    |
| Specifications (Main)    | ϕ168×5 mm |
| Specifications (Branch) to Zone C and D | ϕ114×4.0 mm |
| Specifications (Branch) to zone B  | ϕ60×3.5 mm |
| Insulation Thickness     | 100 mm   |

Figure 1. The steam piping site layout
The stress state of the pipeline system can be calculated by simulating different working conditions. After checking the 3D model, software calculated the ratio of primary stress and secondary stress to allowable stress and pipeline thermal displacement at each node. The result of analysis and calculation were shown in Table 2 and Table 3 (W=the pipeline and steam weight).

| Name | Node | Code | Stress/ MPa | Allowable Stress/ MPa | Ratio/ % | Working condition |
|------|------|------|-------------|-----------------------|---------|-------------------|
| L4   | 550  | 51.2 | 135.4       | 37.8                  | W+P1    |
| L6   | 794  | 114.1| 328.7       | 34.7                  | L3-L4   |

Table 3. Maximum displacement

| Name | Node | DX/ mm | DY/ mm | DZ/ mm | NOTE | Working condition |
|------|------|--------|--------|--------|------|-------------------|
| L3   | 67   | +67.9  | -6.6   | -25.4  | DX Max| W+T1+P1          |
| L3   | 698  | +2.2   | -0.1   | -97.3  | DZ Max| W+T1+P1          |

4. Inspection scheme

The inspection based on stress analysis took the stress data in pipeline system as the basis of risk division. Firstly, the ratio of calculated stress to allowable stress was taken as the value of risk. Then according to certain rules (See Table 4) for the classification of risk levels, the weak nodes of pipeline were found. Finally, targeted inspection programs were made for high-risk nodes, which can prolong the inspection period of low-risk nodes, reduce the cost and improve the inspection efficiency [6].

| Risk level | Risk area | Ratio/ % |
|------------|-----------|----------|
| I          | Lower Risk| 0~20     |
| II         | Low Risk  | 20~40    |
| III        | Medium Risk| 40~60   |
| IV         | High Risk | 60~80    |
| V          | Higher Risk| >80     |

The risk level of each node evaluated on both the primary stress risk level was R1, and secondary stress risk level was R2 of each node. The comprehensive risk level of the node, R0, was the larger value between R1 and R2. This assessment involved a total of 144 nodes. According to the stress state of each node calculated by the software, R1 and R2 only contained risk levels I and II, no levels III to V. The results showed that R0 was low. The calculated data were collated in Table 5.

| Name | Level I Quantity/Ratio | Level II Quantity/Ratio | Total Nodes | Level II Position |
|------|------------------------|-------------------------|-------------|------------------|
| R1   | 107/74.3%              | 37/25.7%                | 144         | Supports and endpoint elbow |
| R2   | 134/93.1%              | 10/6.9%                 | 144         | Elbows           |
| R0   | 97/67.3%               | 47/32.4%                | 144         |                  |

Further analysis found that risk level II of R1 were located in supports and endpoint elbows, and risk level II of R2 were located in the elbows of self-compensation structure (See the circular area in Figure 1). The supports and elbows were the important part need to focus on. Thickness Testing, Radiographic Testing and Magnetic Particle Testing were used for welds inspection of the elbows with large stress. The number of elbows inspected was not less than 30% of the total amount. And the conditions of the supports such as corrosion, stripping, deformation also need to be visually checked.
5. Conclusions
The software CAESAR II was used to build the model of pipeline and reliable theoretical calculation data were obtained. The results showed that the primary stress and secondary stress of the steam pipeline met the requirements of ASME B31.3-2016. The software calculated that the position with the greatest primary stress was at the nodes of the support and the greatest secondary stress was at the elbow. Compared with the traditional random sampling method, the inspection based on stress analysis is an innovative test method. Based on the results of the calculation, the risk can be detected in advance. Targeted inspection programs can minimize the risk.

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