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Analysis on the Leakage of the Flange Connection of the Water-Containing Hydrofluoric Acid Pipeline

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Abstract: Leakages of bolted pipe flange connections of water-containing hydrofluoric acid pipelines were frequently reported by the extraction section in the fluorine chemical industry. Water-containing hydrofluoric acid can cause severe injuries to human beings due to its strong causticity. The water-containing hydrofluoric acid pipe was a short lined pipe, so a lot of flange connections and supports were adopted in the pipeline. In this paper, the finite element models of the pipeline were established to analyze the internal force of the pipeline under conditions including internal pressure, temperature, self-weight, and so on. Based on this, the equivalent design pressure of the flange connections was determined. The results of the stress analyses of the pipeline showed that leakages were mainly caused by a large bending moment, due to the unreasonable layout of the piping supports under self-weight. When the pipeline was supported on the beam of the pipe gallery, which is not necessarily beneficial to reduce the bending moment of the pipeline, and the flange connection was close to the supporting beam at the same time, leakages frequently occurred in this flange connection. To support the pipeline reasonably, the flange connection should be placed at zero bending moment positions. Therefore, the positions with zero bending moments of the pipeline with equal and unequal spacing supports were obtained under gravity load, to provide a basis for the rational support of lining piping.

Keywords: hydrofluoric acid; stress analysis of pipeline; pipe flange connections; leakages

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1. Introduction

Flanges were often reported to leak for various reasons, such as internal pressure [1], piping load due to thermal deformation [2,3], aging of gaskets [4], and creep or stress relaxation of the bolt and flange under high temperatures and high pressures [5–7]. In fact, the leakage of the flange sealing was the result of multiple factors [8]. Therefore, leakage analysis is required for piping systems under relatively high temperatures and pressures [9]. However, piping lines under low pressure and mild temperature often escape from the strict scrutiny of piping stress analysis by experience [10]. However, for piping lines convening a highly hazardous medium, leakage analyses are also essential for human safety. Water-containing hydrofluoric acid can cause severe injuries to human beings due to its strong causticity, but leakages of bolted pipe flange connections of the water-containing hydrofluoric acid pipeline were frequently reported in the fluorine chemical industry. Consequently, it is important to quickly estimate the leakage risk of flange connections of the pipeline under low pressure and mild temperature. The strength design of the beam is often concerned with the maximum bending moment section. Similarly, pipeline stress analysis also focuses on the maximum bending moment point to check the pipeline strength or the sealing performance of the flange connection at corresponding positions. In this paper, the internal force of the water-containing hydrofluoric acid pipeline will be analyzed under conditions of internal pressure, temperature, and self-weight to find the main cause of the bending moment and methods of reducing the bending moment to ensure good performance of the flange sealing.

According to the investigation into Fluorine Chemical Co., Ltd. (Quzhou, China), it was found that several leakages occurred in the flange connections of the water-containing hydrofluoric acid pipeline, from the outlet of the delivery pump to the extractor in the extraction section of R134A. The pipeline works under a pressure of 0.9 MPa (the conveying pump head is 90 m) and a temperature of 12 °C. It was a carbon steel pipe with PTFE lining to convey the 40% hydrofluoric acid. The lining pipe length was 2 m and flanges were used to connect two lining pipes (as shown in Figure 1). The flanges were flat welded plate flanges with a nominal pressure of PN10 and a nominal diameter of DN40, whose sealing surfaces were raised flat surfaces. The layout of this pipeline, connecting the delivery pump (P-A362) to the extraction tank (near V-A351B), is shown in Figure 2. The pipes of the delivery pump and the east–west pipes were both supported in the vertical direction, with an interval of about 2 m, but the north–south pipe (whose length was 8.5 m) was not supported. Leakages of the flange connection mostly occur on the east–west pipe, which was 28 m in this pipeline.

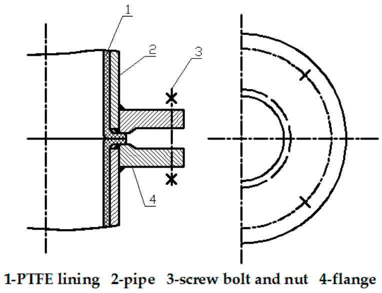


Figure 1. Pipe flange connection diagram.

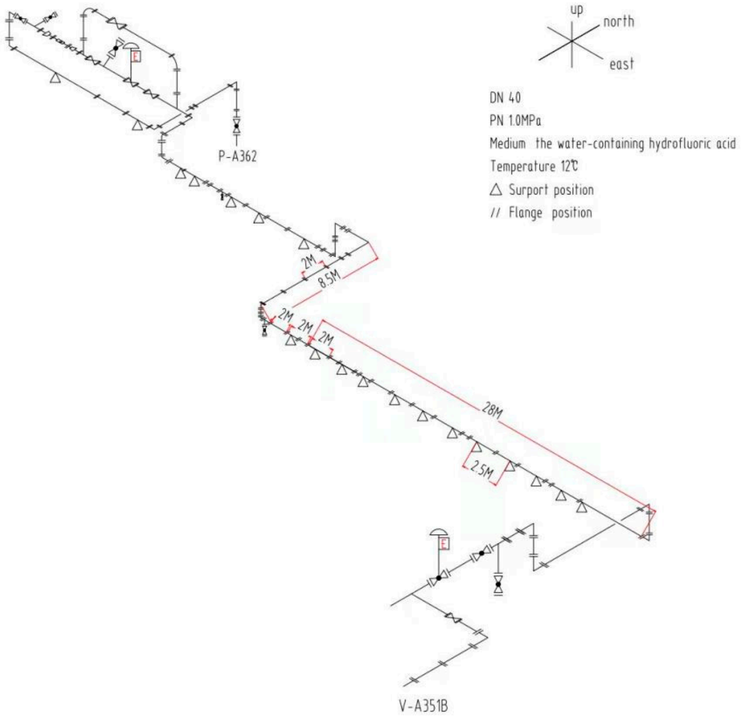


Figure 2. Axonometric drawing of pipeline.

The equivalent stress method, NC3658.3 method, and ASME B&PVC specification VIII-I appendix 2 are the three mature flange leakage analysis methods that are widely used at present. The first two methods are mainly used for flanges under general working conditions, without high temperatures or high pressures [11]. The water-containing hydrofluoric acid pipeline worked under a pressure of 0.9 MPa and a temperature of 12 °C, so the equivalent pressure method can be used to evaluate the flange leakage.

The equivalent pressure method converts external loads, such as the axial force and bending moment of the flange, into equivalent pressure, then adds the equivalent pressure and the design pressure to obtain the total pressure. Finally, the total pressure is compared with the allowable pressure in the temperature and pressure table related to the flange material in ASME B16.5. It is theoretically considered that when the total pressure is less than the allowable pressure given in the standard, the flange will not leak; otherwise, it will leak.

The pipeline vibration is not considered in the equivalent pressure method. The leakage of the flange connection near the pump outlet is closely related to vibration [12], so it is necessary to consider the impact of vibration on the performance of the gasket. However, leakages of flange connections mostly occurred on the east–west pipe in the water-containing hydrofluoric acid pipeline, and the leak's location was far away from the pump outlet. Therefore, vibration is not the primary cause of leakage in this case, and the vibration of the pipeline was not considered in the current study.

For this kind of pipeline, the length of the lining pipe was short and many flange connections were used in the piping. When many supports are used in the pipeline, it may be beneficial to improve the sealing performance of the flange by reasonably supporting the pipeline and placing the flange at a position with a low bending moment. The most ideal state would be that in which the flange connection is located in positions of zero bending moment. Therefore, the positions of zero bending moment of the pipeline with equal and unequal spacing supports were obtained, to provide a basis for the rational support of lining piping.

2. Finite Element Modeling

ANSYS finite element software was used for modeling [13]. The Pipe16 element, Pipe18 element, and Link180 element of ANSYS were used for straight pipe, bend pipe, and support, respectively. The internal pressure of the pipeline was 0.9 MPa, the temperature was 12 °C, the density of 40% water-containing hydrofluoric acid was 1130 kg/m^3, the density of the carbon steel pipe was 7850 kg/m^3, the elastic modulus was 2×10^5 MPa, the Poisson's ratio was 0.3, and the linear expansion coefficient was $10.85 \times 10^{-6}/°C$ [14]. PTFE lining was ignored in the finite element analysis.

As shown in Figure 3, the end of the pump outlet and the extractor are fully constrained, and the bottom of the supports are constrained in the vertical direction. The gravitational acceleration was 9.81 m/s^2, set in the Z direction.

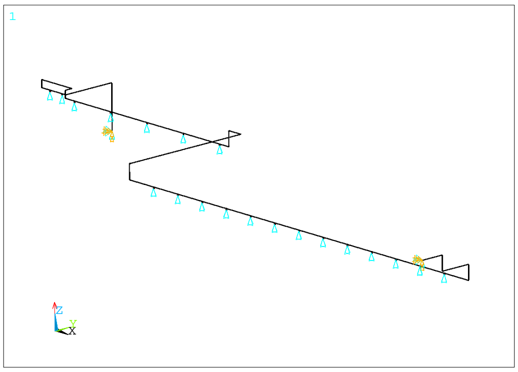
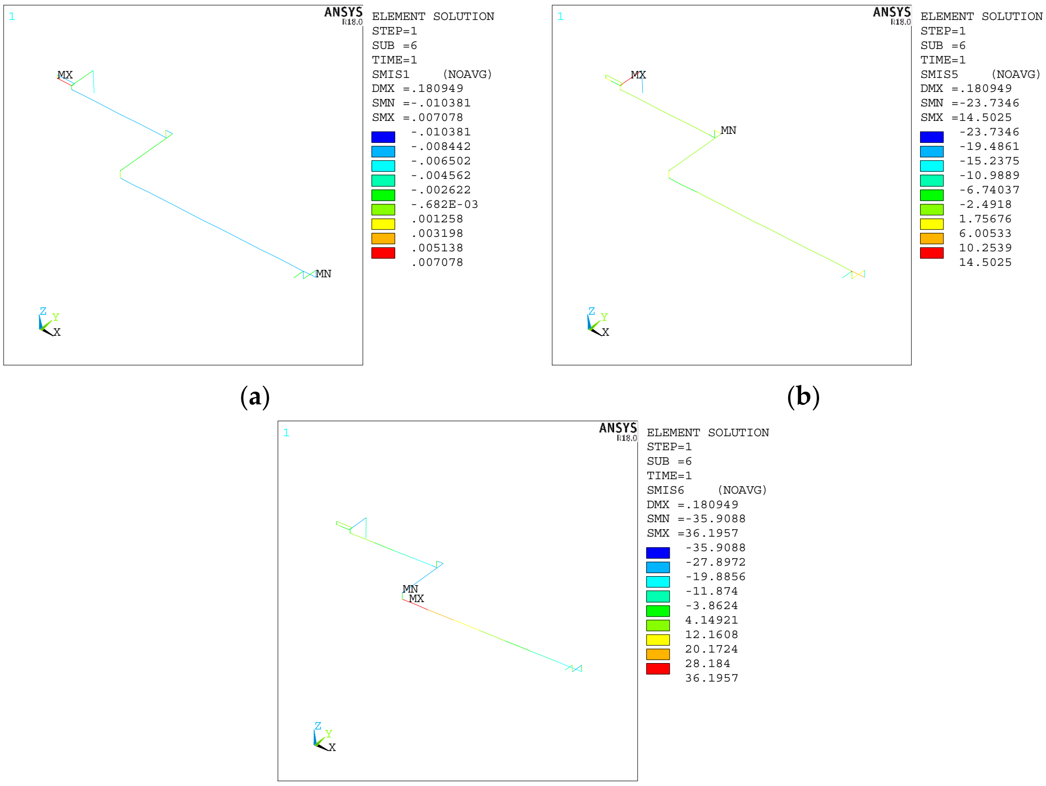


Figure 3. Element model of pipeline.

3. The Calculation Results

Without taking into account the gravity of the pipelines, the calculation results of the axial force and bending moment are shown in Figure 4. The units of axial force and bending moment in the figure are N and N·mm, respectively. As shown in Figure 4, the axial force and bending moment of the piping are very small when only considering the internal pressure and temperature, so their influence on the sealing performance of the flange connection can be ignored. However, when gravity is considered, as shown in Figure 5, a larger bending moment can be generated in the pipeline. The maximum bending moment M_y, whose value is 4.4025×10^5 N·mm, is located in the east–west pipe. The M_z at this position is 0.18205×10^5 N·mm, so the combined bending moment is 4.4063×10^5 N·mm. The axial force at this position is 3.42 N.



(**a**) (**b**)

(**c**)

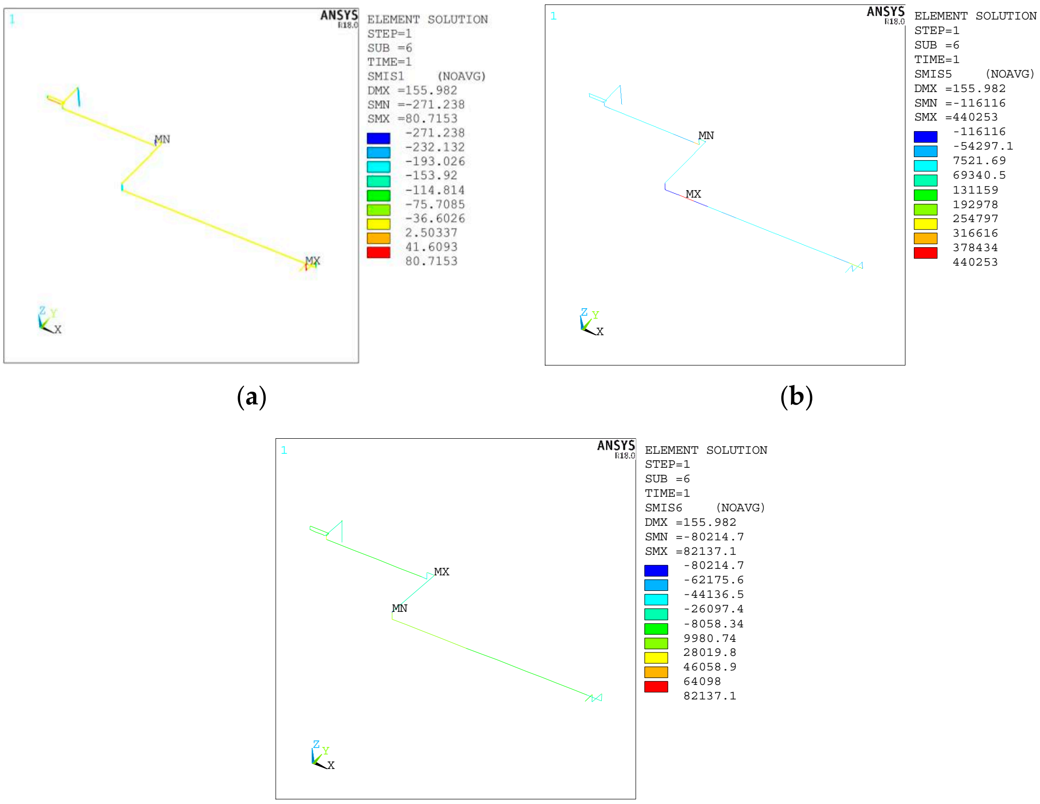
Figure 4. Axial forces and bending moments of piping when ignoring gravitation: (**a**) axial force (N); (**b**) bending moment M_y (N·mm); (**c**) bending moment M_z (N·mm).

The equivalent calculated pressure p_e of the flanges can be expressed as follows [15]:

$$p_e = p_c + \frac{4F}{\pi D_G^2} + \frac{16M}{\pi D_G^3} \tag{1}$$

where p_c is the design pressure, F is the reaction force of the support, M is the bending moment, and D_G is the diameter of the compaction center circle of the gasket. For the flat welding flange with PN10, DN40, a raised flat surface, and a PTFE gasket, D_G can be obtained as 75.41 mm [16].

When p_c was 0.9 MPa, p_e was 6.13 MPa. The maximum allowable working pressure of the flat welding flanges of carbon steel with a nominal pressure of 10 bar at 12 °C was 1.0 MPa [15], which was smaller than p_e, so the flange connection cannot meet the sealing requirements.



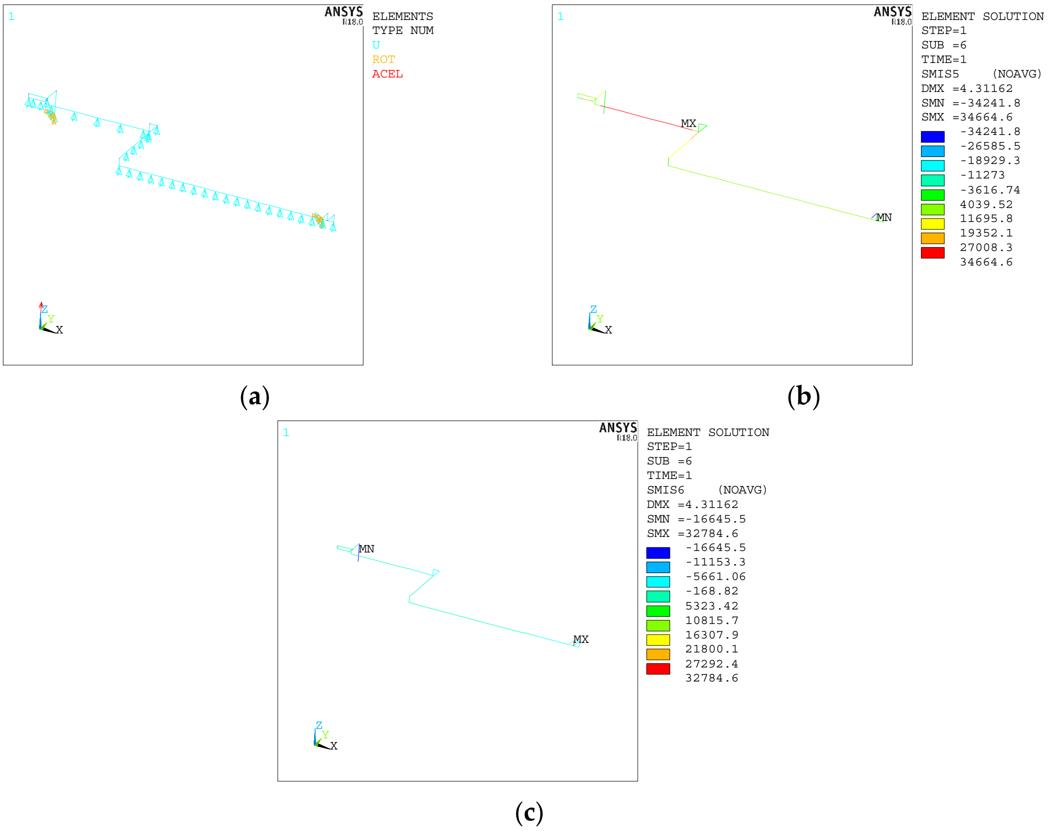
(**a**) (**b**) (**c**)

Figure 5. Axial forces and bending moments of piping when considering gravitation: (**a**) axial force (N); (**b**) bending moment M_y (N·mm); (**c**) bending moment M_z (N·mm).

4. Analysis and Discussion

From the above analysis, it was found that, due to the effect of the pipe load (bending moment), the equivalent calculated pressure of the flange was far higher than its maximum allowable working pressure. The excessive bending moment was mainly caused by the gravity of the pipeline, especially in the case of the north–south pipe not being supported in the middle. The bending moment of the pipeline can be significantly reduced by increasing the supports for the north–south pipe, thus the equivalent calculated pressure of the flange decreased. In this way, the flange connection can meet the requirements of sealing by appropriately increasing the nominal pressure of the flange.

The north–south pipe was evenly supported in the vertical direction, with an interval of about 2 m, and the finite element model and calculation results after adjusting the supports of the pipeline are shown in Figure 6. It can be observed from Figure 6 that the maximum bending moment M_y is 34,665 N·mm and M_z is 180.1 N·mm at the same position, which are significantly lower than the original value. As a result, the maximum equivalent calculation pressure of the flange was 1.24 MPa, which could meet the sealing requirements when PN16 was chosen as the nominal pressure of the flange.



(**a**) (**b**)

(**c**)

Figure 6. The improved finite element model and calculation results: (**a**) finite element model; (**b**) bending moment M_y (N·mm); (**c**) bending moment M_z (N·mm).

To support the pipeline reasonably, the flange connection should be placed at zero bending moment positions. Linear elastic static analysis of the pipeline with equal and unequal spacing supports will be conducted to determine their positions of zero bending moment.

The mechanical model of the pipeline with non-equal spacing supports is shown in Figure 7. The uniformly distributed load due to gravity is q, the bending moments of the mid-span section are M_1 and M_2, and that of the supporting sections is M_3. F is the reaction of support. Taking the support position as the origin, the bending moment equation of both sides can be calculated by Equations (2) and (3), respectively.

$$M = M_1 - \frac{q(L_1 - \mathrm{x})^2}{2} \qquad (0 \le x \le L_1) \tag{2}$$

$$M = M_2 - \frac{q(L_2 + \mathrm{x})^2}{2} \qquad (-L_2 \le x \le 0) \tag{3}$$

where L_1 and L_2 are half of the span on both sides of the supports, respectively. For discussion purposes, we supposed that L_1 was greater than L_2.

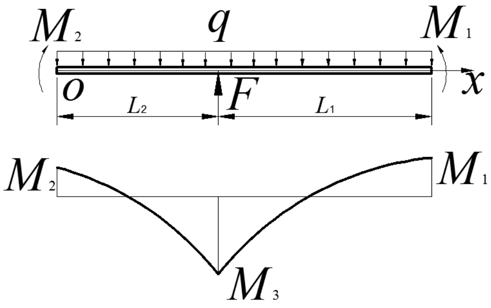


Figure 7. The mechanical model of the pipeline with non-equal spacing supports.

Setting the deflection of the beam as w, the following two expressions can be obtained:

$$\frac{d^2w}{dx^2} = M_1 - \frac{q(L_1 - \mathrm{x})^2}{2} \qquad (0 \le x \le L_1) \tag{4}$$

$$\frac{d^2w}{dx^2} = M_2 - \frac{q(L_2 + \mathrm{x})^2}{2} \qquad (-L_2 \le x \le 0) \tag{5}$$

According to the deformation compatibility conditions of the angle being zero on the symmetric interface (mid-span section), namely, $\left.\frac{dw}{dx}\right|_{x=L_1} = 0$ and $\left.\frac{dw}{dx}\right|_{x=-L_2} = 0$, the integral constant can be determined, so the two following equations can be obtained:

$$\frac{dw}{dx} = \frac{q(L_1 - \mathrm{x})^3}{6} - M_1(L_1 - \mathrm{x}) \qquad (0 \le x \le L_1) \tag{6}$$

$$\frac{dw}{dx} = M_2(L_2 + \mathrm{x}) - \frac{q(L_2 + \mathrm{x})^3}{6} \qquad (-L_2 \le x \le 0) \tag{7}$$

For x = 0, the value calculated by Equations (4) and (5) should be the same, so the following applies:

$$M_1 = M_2 + \frac{q(L_1^2 - L_2^2)}{2} \tag{8}$$

Similarly, for x = 0, the value calculated by Equations (6) and (7) should be the same, so the following applies:

$$M_1L_1 + M_2L_2 = \frac{q(L_1^3 + L_2^3)}{6} \tag{9}$$

According to Equations (8) and (9), the bending moments of the mid-span section can be obtained with the following equations:

$$M_1 = \frac{q[(L_1^3 + L_2^3) + 3L_2(L_1^2 - L_2^2)]}{6(L_1 + L_2)} \tag{10}$$

$$M_2 = \frac{q[(L_1^3 + L_2^3) - 3L_1(L_1^2 - L_2^2)]}{6(L_1 + L_2)} \tag{11}$$

In this instance, according to Equation (2), the bending moments of the supporting sections (x = 0) are given by the following:

$$\begin{gathered} M_3 = M_1 - \frac{qL_1^2}{2} \\ = \frac{q[(L_1^3+L_2^3)-3(L_1+L_2)(L_1^2+L_2^2-L_1L_2)]}{6(L_1+L_2)} \end{gathered} \tag{12}$$

According to the Equations (2) and (3), the section position with zero bending moment can be determined by the following equations:

$$M_1 - \frac{q(L_1 - \mathrm{x})^2}{2} = 0 \qquad (0 \le x \le L_1)$$

$$M_2 - \frac{q(L_2 + \mathrm{x})^2}{2} = 0 \qquad (-L_2 \le x \le 0)$$

Therefore, the distance from the section with zero bending moment to the support point was proposed as follows:

$$x_{\mathrm{M}=0} = L_1 - \sqrt{\frac{(L_1^3 + L_2^3) + 3L_2(L_1^2 - L_2^2)}{3(L_1 + L_2)}} \qquad (0 \le x \le L_1) \tag{13}$$

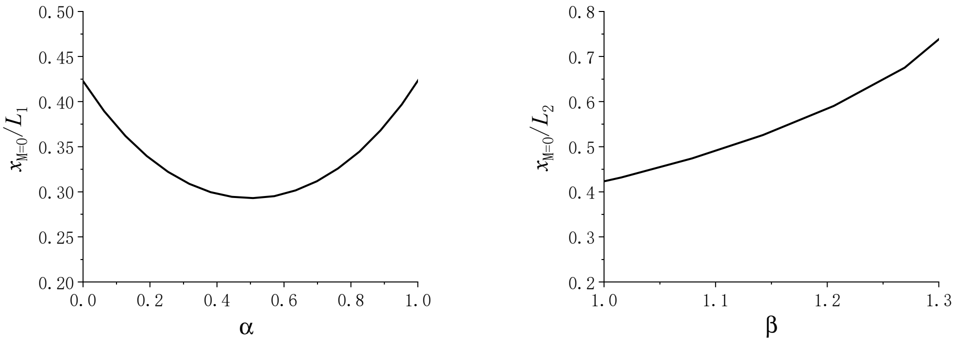
$$x_{\mathrm{M}=0} = L_2 - \sqrt{\frac{(L_1^3 + L_2^3) - 3L_1(L_1^2 - L_2^2)}{3(L_1 + L_2)}} \qquad (-L_2 \le x \le 0) \tag{14}$$

Setting $L_2/L_1 = \alpha$, $L_1/L_2 = \beta$, Equations (15) and (16) can be stated as the following:

$$\frac{x_{\mathrm{M}=0}}{L_1} = 1 - \sqrt{\frac{(1+\alpha^3) + 3\alpha(1-\alpha^2)}{3(1+\alpha)}} \qquad (0 \le x \le L_1) \tag{15}$$

$$\frac{x_{\mathrm{M}=0}}{L_2} = 1 - \sqrt{\frac{(1+\beta^3) - 3\beta(\beta^2-1)}{3(1+\beta)}} \qquad (-L_2 \le x \le 0) \tag{16}$$

The variation in the position of the section where the bending moment is zero with α and β is shown in Figure 8. As observed in Figure 8, the distance from the section with zero bending moment to the support point decreased firstly, and then increased with the increasing α on the long-span side. However, on the short-span side, it increases monotonically with the increasing β. It is worth noting that a section with zero bending moment does not always exist on the short-span side. When the value of β is greater than 1.37, the bending moment M_2 is less than zero, and the section with zero bending moment will not appear on the short-span side.



(**a**) (**b**)

Figure 8. The position of the section with zero bending moment: (**a**) long-span side; (**b**) short-span side.

For more complex relationships, the position of the section with a zero or small bending moment can be determined by the numerical calculation, where the flange connection can be arranged.

For a uniformly loaded continuous beam of several equal spans, the moment over each support, and the position of the maximum moment and the points of inflection, have been given in some books (or online resources) on the strength of materials [17]. However, when the equal span support number is large enough, the mechanical model for an equal supporting region that is far away from the piping ends can be reduced to similar ones, as shown in Figure 7, but with the same end moment $M_1 = M_2$. As $L_2 = L_1 = L/2$, according to Equation (15), $x_{\mathrm{M}=0} = 0.211L$. It is interesting that the positions of the zero bending moment in such a case are the same as the beam fixed at both ends [18]. This may be due to the rotation angles at both ends of a beam subjected to uniform load are all zero.

As the influence of the distal boundary of the pipeline was not considered in the mechanical model, the method in this paper is only applicable to determine the zero bending moment position in a region far away from the ends of the pipeline.

For the pipeline discussed in this paper, the flanges should be kept away from the mid-span section and the support point (the positions circled in red, as shown in Figure 9). If the flanges have to be fitted in these positions, it is necessary to conduct pipe stress analysis to ensure that the flange has a good sealing performance.

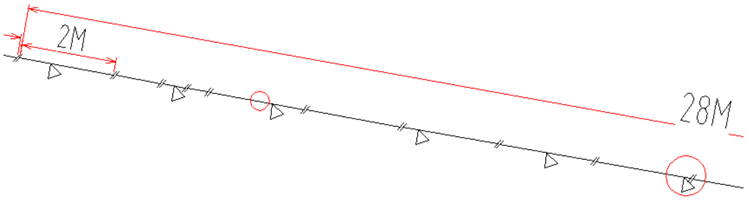


Figure 9. Possible location of leaked flange.

In addition, the outlet pipeline near the pump will be affected by the vibration load of the centrifugal pump, which can cause alternating gasket stresses and may possibly lead to the accumulation of cyclic plasticity in the gasket, namely ratchetting effect. At the same time, the sealing specific pressure will be reduced, to a certain extent, after a long time, due to the creeping of the PTFE gasket under the high preloading force, which depends on the creep performance of PTFE, packing force, packing time, and temperature, and, finally, this results in the sealing failure of the flange connections [4,12]. Such a failure often occurs at the flange circled with red in Figure 10, which was affected by pump vibration. Therefore, in order to solve the leakage problem due to the creep and ratchet effect of the pure PTFE gasket, the stainless steel and PTFE spiral wound gasket was also suggested.

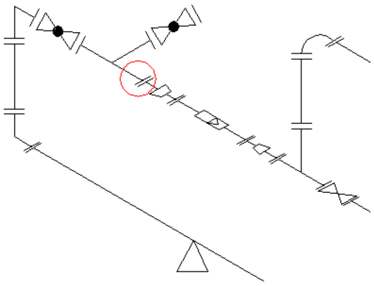


Figure 10. Leakage of the flange near pump outlet.

5. Conclusions

The length of the pipes with PTFE lining, for conveying water-containing hydrofluoric acid in the fluorine chemical industry, were so short that flanges were used to connect the pipes. A larger bending moment, caused by the gravity of the pipeline with improper support, is generated in the flange connection and causes the equivalent calculation pressure of the flange to exceed its maximum allowable working pressure. Therefore, the leakage of strongly corrosive media in the pipeline will occur. In order to ensure the sealing requirements of the flange connection, stress analyses must be carried out for such pipelines, and the support's position should be adjusted reasonably during the pipeline design. For pipelines with equal spacing supports, it was recommended that the flange connection should be located in the position that is approximately 0.211 times the span from the support point, where the moment caused by gravity is close to zero. For the pipelines with unequal spacing supports, the position where the bending moment is zero can be determined by the ratio of two halves of the span on both sides of the supports, and the flange connection should be arranged on these positions.

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