Evaluation of Metal Sealing Performance of High Pressure Casing Hanger under Annular Pressure Conditions

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Abstract. In order to determine the sealing performance of metal seals of ultra-high pressure casing hanger under annular pressure conditions. An equation for the contact pressure of metal seals is derived. A finite element model is developed by fully considering the excitation process of seals and the effect of annular pressure. Based on the model, the sealing performance of metal seals under different annular pressures is analyzed. The results show that metal seals are in a plastic state after excitation; Under the high annular pressure, the maximum Mises stress of the seals was 241MPa and 225MPa, respectively; the pressure never penetrated seals, and the sealing performance is excellent. This study provides technical support for the safe working of metal seals of ultra-high pressure casing hanger.

Keywords: Casing hanger; Seal performance; metal seals; Annular pressure

1 Introduction

With the development of oil and gas exploration technology, the number of high-temperature and high-pressure oil and gas Wells is increasing [1,2], especially in the complex formations in Sichuan and Tarim basins, and the problem of wellbore integrity becomes particularly prominent [3]. Under these harsh operating conditions, casing hangers in wellhead installations face great challenges. Due to deep reservoir burial, high formation pressure, high temperature, and the presence of corrosive gases such as CO_2 and H_2S [4], the working environment of wellhead seal is extremely harsh. Traditional rubber seals are prone to aging in this environment, resulting in annular pressure that affects well integrity and can pose serious safety and environmental concerns.

Therefore, the high pressure casing hanger metal is studied the sealing performance of seals is of great practical significance for improving the safety of oil and gas Wells and prolonging their service life [5].

In view of the sealing performance of metal seals of high pressure casing hangers, scholars have done related research. Smith et al. [6] developed a new spherical sealing structure, which greatly improved the sealing ability. Ma et al. [7] studied that welding a layer of steel wire components on the sealing surface of the all-metal sealing ring can effectively solve the problem of gas leakage caused by insufficient clamping force during the loading and unloading of metal seals. Huang et al. [8] analyzed that the sealing structure of the oil pipe hanger also achieves the sealing between metals by stimulating the deformation of the elastic body, so that the sealing function between metals can be effectively realized. Li et al. Peng et al. [9] compared and analyzed the contact pressure distribution of cylindrical to spherical and cone-to-cone metal sealing structures under different tensile and torque conditions, and proposed that cone-to-cone sealing structures are more conducive to improving the sealing performance of threaded structure sealing surfaces. [10] found that the greater the thickness of metal C-ring alloy coating layer, the more uniform the contact pressure distribution, the smaller the contact width, and the smaller the plastic strain on the gold coating. These results provide certain method guidance for the improvement of metal seal structure of hangers.

In the field of metal sealing, despite a large amount of research focusing on its basic theories and applications, there are still certain shortcomings in the comprehensive evaluation of metal sealing performance under high-pressure conditions, especially regarding the behavior of metal sealing components in high-pressure casing hangers under annular pressure. Existing studies mostly emphasize performance analysis under conventional pressure conditions, lacking in-depth exploration of the plastic deformation behavior of metal sealing components under high-pressure environments and its impact on sealing effectiveness. Based on this research gap, this paper derives the calculation equation for the contact pressure of metal seals and establishes a finite element evaluation model for metal seals in ultra-high pressure casing hangers. By analyzing the changes in metal seal performance under different annular pressures, this paper reveals the plastic deformation characteristics of metal seals in high-pressure environments and the impact of these deformations on sealing performance.

2 Mechanical Model

The metal sealing ring of the casing hanger adopts a C-shaped metal sealing structure, and its contact can be approximately equivalent to that of two cylinders contacting each other. According to the Hertz contact theory, it is obtained that when two cylinders are in contact under normal force F, the half width (r) of the contact surface and the maximum contact stress (δ_{Hmax}) are respectively

$$r = \sqrt{\frac{4F\left(\frac{1-\mu_1^2}{E_1}+\frac{1-\mu_2^2}{E_2}\right)}{\Pi b\left(\frac{1}{\rho_1}\pm\frac{1}{\rho_2}\right)}} \tag{1}$$

$$\delta_{H\max} = \sqrt{\frac{F}{\Pi b}\left(\frac{\frac{1}{\rho_1} \pm \frac{1}{\rho_2}}{\frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2}}\right)} \tag{2}$$

Where ρ_1 and ρ_2 are the radius of curvature of the two cylinders or the radius of the two spheres,b is the length of the contact line of the two cylinders,$E_1$and E_2 are the elastic modulus of the two contact objects, and and represent the Poisson's ratio of the two materials respectively.

First of all, the contact stress formula and the half-width formula of the contact surface are simplified, and the thickness is 1 mm in the calculation. When $\mu_1 = \mu_2 = 0.3$, $\mathrm{E1} = \mathrm{E2} = \mathrm{E}$, the formula for calculating the maximum contact pressure and contact half-width can be simplified as follows:

$$\delta_{H\max} = 0.418\sqrt{\frac{FE}{b\rho_1}} \tag{3}$$

$$r = 1.522\sqrt{\frac{F\rho_1}{Eb}} \tag{4}$$

In practical application, the sealing ring is considered to be affected by interference fit and oil and gas prepressure. These two forces are expressed as F1 and F2 respectively, F1 is the squeezing effect of interference fit on the seal ring during the sealing process, and F2 is generated by the internal oil and gas prepressure.

Then these two forces are simplified into two kinds of force models. F1 can simplify the sealing ring model to the cantilever beam model for calculation, using the relationship between the concentrated force (F)and Deflection($w_{\max}$) to solve theF1. F2 can simplify the sealing ring model to a simple supported beam structure for calculation, using the same relationship to solveF2.

$$F_2 = qc + q(d+h)\cos\alpha + \frac{q\left(\frac{h^2-d^2}{2}\right)\cos\alpha - q\left(cd+\frac{c^2}{2}\right)}{c+d} \tag{5}$$

Finally, by substituting equation 5 and equation 4 into equation 3, the analytical expression of the maximum contact pressure can be obtained as follows:

$$\delta_{\mathrm{Hmax}} = 0.418\sqrt{\left[\mathrm{k}_1\left(\frac{6\mathrm{EII}_{\max}}{(3\mathrm{l}-\mathrm{a})\mathrm{a}^2}\right) + \mathrm{k}_2\left(\mathrm{qc} + \mathrm{q}(\mathrm{d}+\mathrm{h})\cos\alpha + \frac{\mathrm{q}\left(\frac{\mathrm{k}^2-\mathrm{a}^2}{2}\right)\cos\alpha - \mathrm{q}\left(\mathrm{cd}+\frac{\mathrm{c}^2}{2}\right)}{\mathrm{c}+\mathrm{d}}\right)\right]\mathrm{E}} \tag{6}$$

3 Finite Element Model

3.1 Common Seal Structure of the Shaft Core Type Casing Hanger

The research object is the shaft core type casing hanger of a certain manufacturer, as shown in Figure 1 below:

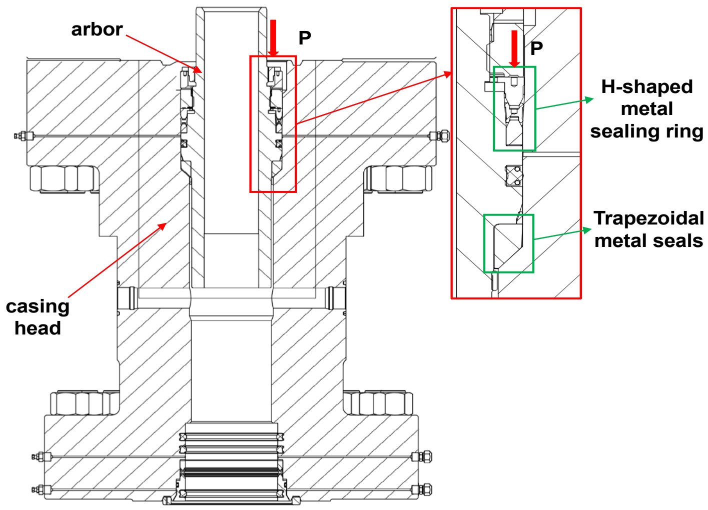

Fig. 1. Conventional Shaft Core Type Casing Hanger and Seal Structure.

Figure 1 shows an H-shaped metal seal hanger, which mainly uses the H-shaped metal seal component and the lower FS rubber seal component to seal the annular space between the core shaft and the casing head. The H-shaped metal seal component has four hemispherical convex surfaces, and when the metal seal ring's four hemispherical convex surfaces are compressed by the upper pressure ring, they will open laterally, thereby sealing the annular space between the core shaft and the manifold. The lower trapezoidal metal seal is extruded and expands laterally under the gravity of the casing string, thus sealing the lower annular space between the core shaft and the manifold.

3.2 Establishment of Seal Structure Model

Based on the overall structure dimensions of the shaft core type casing hanger shown in Figure 1, the modeling research is conducted according to the axisymmetric structure. The geometric analysis model includes the core shaft, manifold, pressure ring, support ring, H-shaped metal seal structure, and lower trapezoidal metal seal structure. During the analysis, a tensile load of F=0~4000kN is applied to the lower end face of the core shaft, and a displacement load of H=0~5mm and a pressure load of P=0~175MPa are applied to the upper end face of the seal pressure ring, as shown in Figure 2.

Basic material mechanics parameters: the material of the core shaft is 718 with a yield strength of 800MPa and a modulus of elasticity of 210GPa; the material of the casing head is 4130 with a yield strength of 835MPa and a modulus of elasticity of 213GPa; the material of the pressure ring and base are 42CrMo with a yield strength of 930MPa and a modulus of elasticity of 210GPa. The materials of the H-shaped metal seal component and the trapezoidal metal seal component are 825 with a yield strength of 241MPa and a modulus of elasticity of 210GPa. Finally, based on the structural design and force model of the shaft core type casing hanger, the load-bearing capacity and sealing performance of the seal structure under different pressures and different casing string gravity are checked.

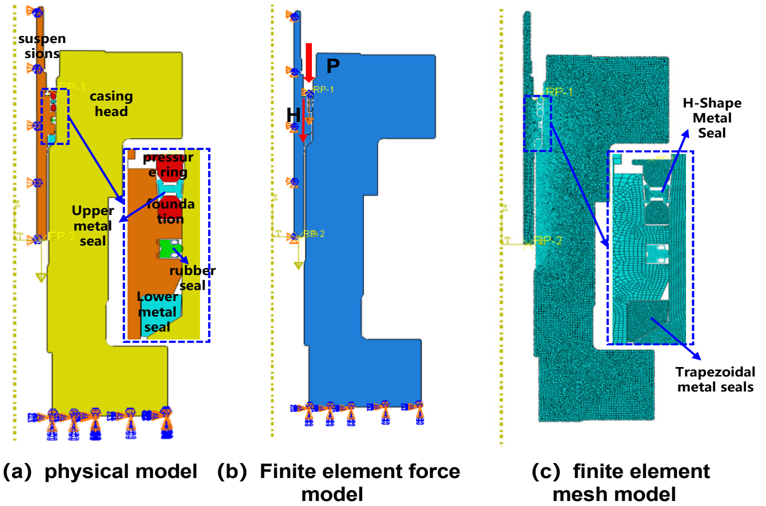

Fig. 2. H-shaped Metal Seal Structure and Finite Element Model.

4 Seal Performance Calculation Results and Analysis

4.1 Metal Seals Sealing Performance Analysis

Influence of Compression Displacement on the Sealing Performance of the H-shaped Metal Seal Component. The sealing performance analysis of the H-shaped metal seal under different downward displacements was conducted separately, and the Mises stress distribution and contact pressure distribution of the H-shaped metal seal structure are shown in Figures 3 and 4 below:

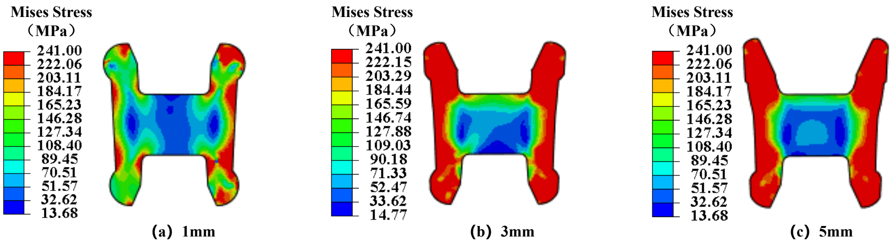

Fig. 3. Mises Stress Distribution of H-shaped Metal Seal under Different Displacement Loads.

As shown in Figure 3, with the increase in the downward displacement load, the stress on the H-shaped metal sealing ring also increases. Among them, the stress changes at the four contact points are more significant, but during the entire downward displacement process, the stress change in the middle part of the H-shaped metal sealing ring is not substantial. When the downward displacement is 1 mm, the maximum Mises stress on the H-shaped metal reaches the material yield strength of 241 MPa, resulting in plastic. When the downward displacement is 1-2 mm, the two contact pairs on the upper half of the H-shaped metal seal deform slightly. However, when the downward displacement is 2-5 mm, all four contact points of the H-shaped metal seal undergo significant deformation. For soft metals, this plastic deformation, although initially helpful in enhancing the sealing effect, may lead to fatigue failure of the seal if the downward displacement is too large, thereby affecting the sealing performance.

Figure 4 shows the variation curves of contact pressure on contact paths 1, 2, 3, and 4 of the H-shaped metal seal under different downward displacements. It can be seen that the contact pressure of the H-shaped metal seal increases with the increase in downward displacement. The contact pressure on contact path 1 varies between 0 and 1385 MPa; the contact pressure on contact path 2 varies between 0 and 1774 MPa; the contact pressure on contact path 3 varies between 0 and 1731 MPa; the contact pressure on contact path 4 varies between 0 and 1853 MPa. Although high contact pressure helps to enhance sealing, it can also lead to excessive deformation of the material, thereby affecting the stability of the seal. Especially under larger displacements, the contact surface may experience severe fluctuations, resulting in unstable sealing performance.

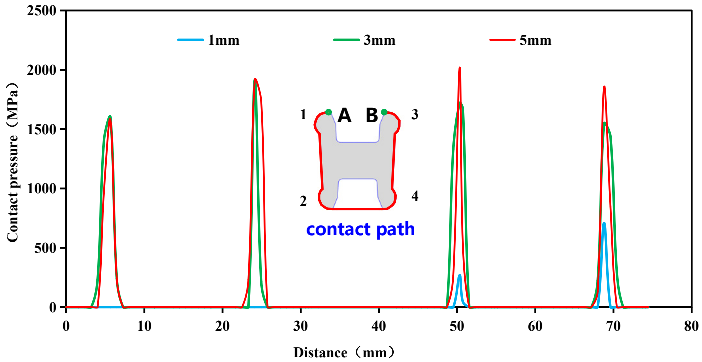

Fig. 4. Contact Pressure Change Curve of H-shaped Metal Seal Component with Compression Displacement.

Influence of Suspended Load on the Sealing Performance of the Trapezoidal Metal Seal Component. Figure 5 shows the Mises stress distribution of the trapezoidal metal seal under different suspended loads. As shown in the figure, with the increase in the suspended load of the casing, the Mises stress on the trapezoidal metal seal also increases, and the Mises stress on the trapezoidal metal seal is mainly concentrated in the lower half where it contacts the casing head. This is due to the fact that under the action of the casing suspended load, a large interaction force is generated between the trapezoidal metal seal and the casing head contact surface. When the casing suspended load is 1000 kN, the maximum stress on the trapezoidal metal seal has reached the material yield strength of 241 MPa, resulting in plastic deformation. Subsequently, as the suspended heavy load continues to increase, the plastic deformation area of the trapezoidal metal seal also continues to expand. Although the plastic deformation of the trapezoidal metal seal helps to enhance its sealing performance, excessive plastic deformation can also affect the stability of its sealing structure, leading to a loss of its original sealing capability.

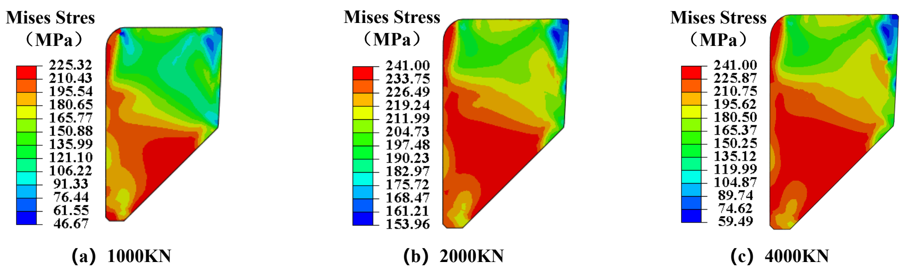

Fig. 5. Mises Stress Distribution of Trapezoidal Metal Seal Component under Different Suspended Loads.

In Figure 6, it can be seen that the contact pressure of the trapezoidal metal seal increases with the increase in suspended load. When the suspended load is between 1000KN and 4000KN, the maximum contact pressure of the trapezoidal metal seal varies between 625MPa and 839MPa. Additionally, it can be seen from the diagram that the contact pressure of the trapezoidal metal seal has significant fluctuations, which may lead to unstable sealing performance of the trapezoidal metal seal.

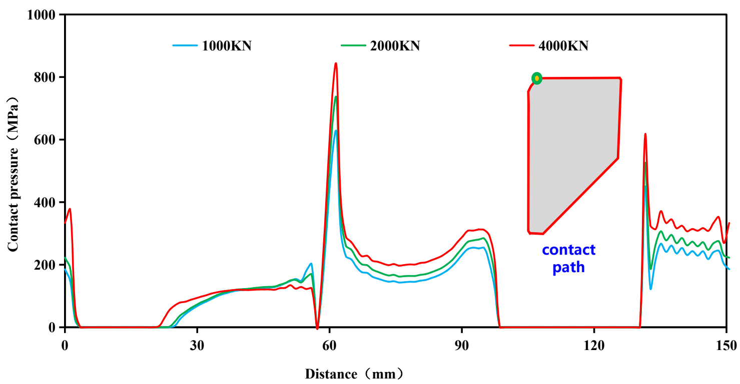

Fig. 6. Contact Pressure Change Curve of Trapezoidal Metal Seal Component with Suspended Load.

4.2 Effect of Different Fluid Pressure Loads on the Sealing Performance of H-Type Metal Seals and Trapezoidal Seals

Additionally, it can be seen from the diagram that the contact pressure of the trapezoidal metal seal has significant fluctuations, which may lead to unstable sealing performance of the trapezoidal metal seal. From Figure 7, we can see that as the fluid pressure load on the lower part of the H-shaped metal seal increases, the Mises stress at the contact area between the lower part of the H-shaped metal seal and the casing head and hanger gradually decreases. This is due to the increase in the lower fluid pressure load, which causes the H-shaped metal seal to experience an upward force from the fluid pressure, thereby reducing the interaction force between the lower part of the H-shaped metal seal and the contact surface of the casing head and hanger. Additionally, from Figure 8, we can see that as the fluid pressure load increases, the contact length between the H-shaped metal seal and the casing and suspensions does not change significantly, the contact pressure on paths 1 and 4 also does not change significantly, but the contact pressure on paths 2 and 3 decreases with the increase in fluid pressure. When the fluid pressure is varied between 50 MPa and 175 MPa, the maximum contact pressure on the H-shaped metal seal contact paths 2 and 3 is reduced from 1770 MPa to 1550 MPa. Although the contact pressure at the bottom of the H-shaped metal seal decreases under fluid pressure load, the overall contact pressure is still greater than the fluid pressure, indicating that the contact performance of the H-shaped metal seal is good. Additionally, from Figure 8, it can be seen that the variation pattern of the contact pressure curve of the H-shaped metal seal shows a wavy line, thus forming a good sealing effect between the contact surfaces.

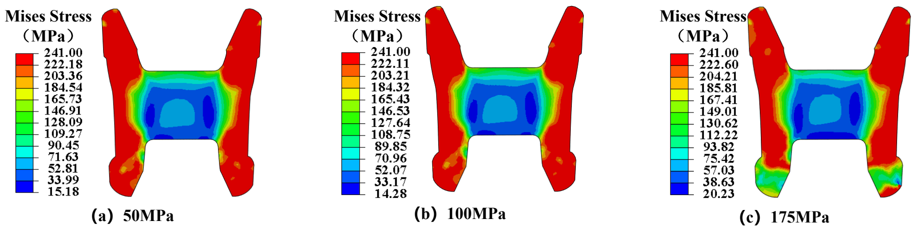

Fig. 7. Mises Stress Distribution of H-shaped Metal Seal Component under Different Fluid Pressures.

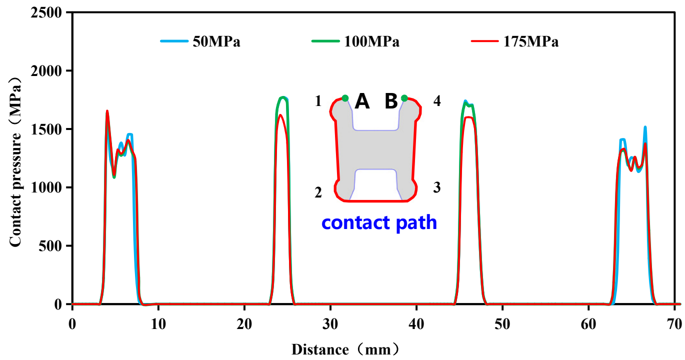

Fig. 8. Contact Pressure Curve Distribution of H-shaped Metal Seal Component under Different Fluid Pressures.

When the trapezoidal metal seal is subjected to a suspended load of 4000KN, different fluid pressures ranging from 0 to 175MPa are applied to the lower part of the trapezoidal metal seal to study the variations in Mises stress and contact pressure of the trapezoidal metal seal. As shown in Figures 9 and 10 below. From Figure 9, we can see that the Mises stress on the trapezoidal metal seal decreases as the fluid pressure load increases. When the fluid pressure is 175 MPa, the maximum Mises stress on the trapezoidal metal seal is 225.32 MPa. This is due to the increase in fluid pressure load on the lower part of the trapezoidal metal seal, which causes an upward force on the contact area between the lower part of the trapezoidal metal seal and the casing head, resulting in a reduction in the interaction force between the lower part of the trapezoidal metal seal and the casing.

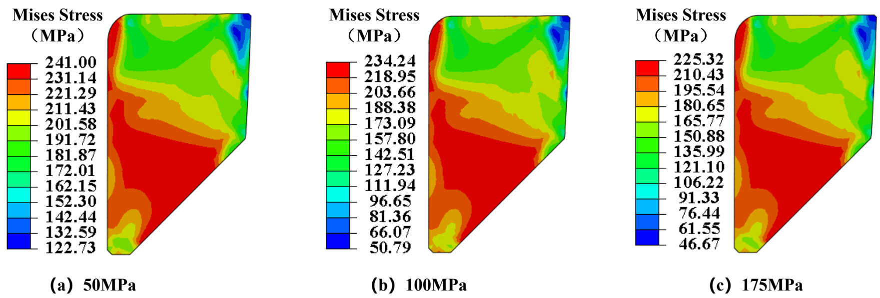

Fig. 9. Mises Stress Distribution of H-shaped Metal Seal Component under Different Fluid Pressures.

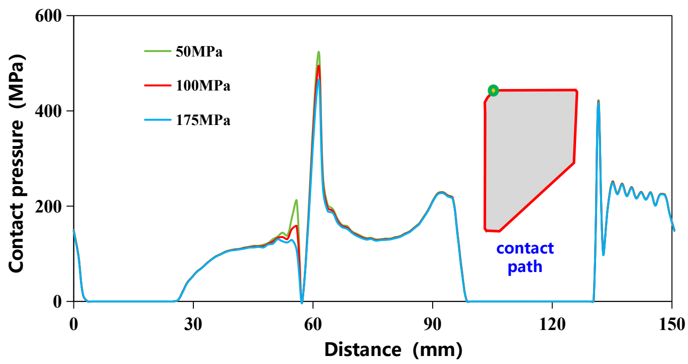

Fig. 10. Contact Pressure Curve Distribution of Trapezoidal Metal Seal Component under Different Fluid Pressures.

From Figure 10, we can see that as the fluid pressure load increases, the overall change in the contact pressure of the trapezoidal metal seal is not significant, but the maximum contact pressure gradually decreases. When the fluid pressure load varies between 50 and 175 MPa, the maximum contact pressure of the trapezoidal metal seal varies between 460 and 520 MPa. The maximum contact pressure is greater than the fluid pressure, indicating that the trapezoidal metal seal can maintain good sealing performance under a fluid pressure of 175 MPa. However, Figure 10 shows that the contact pressure variation curve of the trapezoidal metal seal has a sawtooth pattern with abrupt changes in the middle, indicating that the contact pressure is not stable, and in some areas, there is no contact pressure at all. If the contact pressure does not continue to grow, especially after the fluid load has reached a particular level, the sealing performance will suffer. Combined with the above analysis of the sealing performance of the H-shaped metal seal, research shows that the H-shaped metal sealing ring has good sealing performance. The sealing performance of the overall sealing structure of the casing hanger mainly depends on the sealing length and contact pressure of the four contact surfaces of the H-shaped metal sealing ring.

5 Conclusion

(1) Considering the effect of sealing excitation and annulus pressure, the metal sealing performance evaluation model of casing hanger is established, and the sealing performance evaluation is realized quickly.

(2) The effects of displacement load, suspended load, and fluid pressure on the metal sealing performance are interrelated. Displacement load and suspended load jointly affect the stress distribution and plastic deformation of the seal, while fluid pressure influences the distribution of contact pressure and the stability of the sealing surface. Therefore, in practical applications, to ensure the stability of sealing performance, it is necessary to comprehensively consider the interaction of these factors. Excessive displacement loads and suspension loads may cause the sealing element to undergo plastic deformation, thereby affecting the sealing effect. Fluid pressure should be controlled within a reasonable range to avoid excessive fluctuations in contact pressure.

(3) When designing a metal sealing structure, the shape of the sealing surface and the contact angle should be reasonably designed to ensure that the sealing element can uniformly distribute the contact pressure under different loads, avoiding excessively high local contact pressure. For example, appropriately increasing the contact surface area and reducing stress concentration can effectively improve sealing performance.

(4) Through the analysis of metal seal performance under different annular pressures, it is found that under the high annular pressure, the maximum Mises stress is 241MPa and 225MPa, respectively; the pressure does not penetrate metal seals, and they still have good sealing performance.

References

1. Liu Shujie, Luo Ming, Ma Chuanhua, et al. Safety evaluation method of tubing string under annular trap pressure in deep water high-temperature and high-pressure gas Wells [J]. Science Technology and Engineering, 2019,24(12):4959-4968.
2. Zhang Ting, Yu Yang, Wang Guo, et al. Research and application of gas lift technology in deep Wells containing sulfur in Sichuan-Chongqing area [J]. Natural Gas Exploration and Development,2024,47(04):112-118.

3. Evaluation of air energy storage closure of underground halogen salt chamber in Sichuan Basin [J/OL]. Journal of Southwest Petroleum University (Natural Science Edition), 1-17[2024-12-15]. http://kns.cnki.net/kcms/detail/51.1718.TE.20241120.1434.002.html.
4. Zhang Xiongbin, Dang En, Yu Xiaojing, et al. Research status and progress on corrosion properties of martensitic stainless steel used in oil and gas fields [J/OL]. Chinese Journal of Corrosion and Protection, 1-16 [2024-12- 15]. http://kns.cnki.net/kcms/detail/21.1474.TG.20241106.0902.002.html.
5. Ge Juliang, Yu Xiaotao, Chen Xu, et al. Metal Seal design and Finite Element Analysis of underwater tubing hanger [J]. Petroleum and Chemical Equipment,2024,27(10):13-18.
6. R.R. Smith. New Contoured, Elliptical-Seal Flapper Valve Facilitates API Class II Metal-to-Metal Sealing Performance [C]. Paper OTC-7011-MS Presented at Offshore Technology Conference, 1992, 4-7 May, Houston, Texas.
7. Ma Yongsheng, Guo Dizhou, Jing Yongnan, et al. Methods of metal seal used for ultra-high vacuum system [J]. Vacuum, 2016, 53(6): 9-11.
8. Huang Sidian. Research on Risk Assessment Methods of Tubing Hanger Installation for Horizontal Subsea Christmas Tree[D]. China University of Petroleum,2017.
9. Peng Yu. Study on Sealing Performance of Casing Thread with Metal Seal Principle[D]. Tianjin: Tianjin University of Commerce, 2016.
10. LI Gan, XIE LinJun, LI Zheng, et al. Effect of the Thickness of Alloy Lining on Sealing Performance of Reaction Pressure Vessels Metal C-Ring[J]. Journal of Mechanical Strength, 2018, 40(5):1209-1214.