Sealing Performance Optimization of High Temperature Resistant Steam Sealing Thread of Casing in Heavy Oil Thermal Recovery Well in Xinjiang Oilfield

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Abstract. API trapezoidal thread can not adapt to the high temperature environment of heavy oil thermal recovery in Xinjiang Oilfield. Serious casing damage occurred due to leakage of API trapezoidal thread leakage. In this paper, based on API trapezoid thread structure, a sealing structure with conical surface and shoulder surface were added at the end of the thread. Therefore, a high temperature resistant steam sealing thread (HTRSS thread) suitable for heavy oil thermal recovery well was designed. The influence of the taper of the conical surface and the angle of the shoulder surface on the sealing performance of the thread was analyzed by the finite element method. The sealing structure with the taper of the conical surface of 1/16 and the angle of the shoulder of 10° was optimized. By comparing with the sealing performance of API trapezoid thread and field application, it is verified that the HTRSS thread has excellent sealing performance. The application of the HTRSS thread can effectively reduce the casing damage rate of heavy oil thermal recovery wells and save the heavy oil production cost.

1. Introduction
Xinjiang Oilfield is rich in heavy oil resources, with about 1.1 billion tons of heavy oil realized reserves, which is the main oil area for heavy oil exploitation in China in the coming decades [1]. Steam injection thermal recovery is the main method of heavy oil recovery in Xinjiang Oilfield [2]. The average steam injection temperature of thermal production wells is about 300°C, some of which are up to 350°C. The steam injection pressure is between 10MPa-15MPa [3-5]. In the environment of high temperature and high pressure, the stress of casing in heavy oil thermal recovery well is more complex than that of casing in ordinary well, and the casing in heavy oil thermal recovery well is more likely to fail [6]. Taking Baikouquan heavy oil well area of Xinjiang Oilfield as an example, in the 10 years since its production, 78 wells out of 357 thermal recovery wells have suffered casing damage, accounting for 21.8% of the total number of production wells [7].

Thread is the weak part of casing, thread tripping and leakage are the main forms of casing damage in thermal production wells [8-10]. G Maharaj investigated and analyzed the field data of steam injection...
thermal production wells in a heavy oil field, and found that most casing damage occurred on the casing thread connections [11]. Statistics show that, in a heavy oil field in China, the number of wells with casing thread damaged accounts for 16.4% of the total. API trapezoidal thread is widely used in heavy oil thermal recovery wells, but its thermal stress resistance and high temperature sealing performance are poor, which is one of the important reasons for the thread failure of thermal recovery wells [12-14].

API trapezoid thread seal mainly relies on the contact pressure produced by thread interference fit and thread grease. API trapezoidal thread has spiral clearance between the guide surfaces of the engagement thread and between the top and bottom of the thread, which makes the internal and external of the casing thread spatially connected, resulting in fluid leakage, as shown in Figure 1. The thread grease can prevent the leakage of fluid along the API trapezoidal thread gap in ordinary oil wells, but under the high temperature environment of thermal production wells, the thread grease is damaged or lost, and the sealing capacity of API trapezoidal thread is reduced [15,16].

![Figure 1. Sealing failure of API trapezoidal thread in thermal production wells](image)

In this paper, on the basis of API trapezoid thread, the metal/metal sealing structure is added to design the high temperature resistant steam sealing thread being suitable for heavy oil thermal recovery wells. The taper of the conical surface and the angle of the shoulder surface of the HTRSS thread are optimized by the finite element method. The field application of the HTRSS thread has verified that the HTRSS thread has good sealing performance in the thermal production well.

2. Structure of the HTRSS thread and finite element model

2.1. Structure

In order to improve the sealing performance of thread in thermal production well, the structure of the HTRSS thread suitable for thermal production well is designed, as shown in Figure 2. In the HTRSS thread, it no longer relies on the thread matching to achieve the sealing function, but especially a metal to metal conical surface sealing structure was designed at the end of the thread as the main seal. In addition, in order to avoid over fastening and further increase the reliability of sealing, an annular shoulder surface was also designed at the end of the thread joint as the auxiliary seal. The conical surface sealing structure has the advantages of high contact pressure, long sealing length and easy high-precision machining. The reverse negative angle of shoulder surface was adopted. The negative angle of shoulder surface can improve the self-alignment ability and radial stability of the thread, and the angle of shoulder surface is generally designed as $0^\circ$ ~ $20^\circ$ [17].
2.2. Finite element model

Analysis of thread sealing performance belongs to space mechanics problem. Ignoring the influence of thread spiral angle, the three-dimensional space problem can be treated as two-dimensional axisymmetric problem. The contact analysis is adopted between the threads, and the contact state belongs to face-to-face contact. Considering the pretightening force of thread, casing internal pressure, axial tension, and thermal stress caused by temperature, the finite element analysis model of casing thread in heavy oil thermal recovery well is established, as shown in Figure 3. The boundary conditions of the finite element model are as follows: ① Constrain the radial displacement of the outer wall of the casing coupling; ② Constrain the axial displacement of the shaft end of the casing coupling; ③ Simulate the pretightening force of the thread with the interference amount δ between the teeth of threads; ④ Apply the temperature load T to the inner wall of the casing, and calculate the thermal stress with the thermal sequence coupling method; ⑤ Apply the pressure load P to the inner wall of the casing; ⑥ Apply the axial tensile load F to the end of the casing.
In this paper, the finite element models of the HTRSS thread and the API trapezoid thread are established respectively for comparative analysis of their sealing performance, as shown in Figure 4. The material parameters used in the finite element analysis are shown in Table 1.

### Table 1. Material parameters of casing

| Modulus of elasticity /GPa | Poisson's ratio | Yield strength /MPa | Coefficient of expansion /10^-6·℃^-1 | Specific heat /(J·kg^-1·℃^-1) | Thermal conductivity /(W·m^-1·℃^-1) |
|---------------------------|-----------------|---------------------|-------------------------------------|-------------------------------|-----------------------------------|
| 210                       | 0.3             | 621                 | 12.2                                | 460                           | 45                                |

#### 2.3. Evaluation criteria for sealing performance

(1) Misses stress criterion

In order to avoid plastic deformation of sealing surface and ensure that the structural integrity of the joint, the Misses stress of each part of the joint should be less than the yield limit of the casing material.

$$\sigma_i = \frac{1}{\sqrt{2}} \sqrt{(\sigma_r - \sigma_\theta)^2 + (\sigma_\theta - \sigma_z)^2 + (\sigma_z - \sigma_r)^2} \leq \sigma_s$$

Where: $\sigma_i$ is the Misses stress of casing thread; $\sigma_r$, $\sigma_\theta$, $\sigma_z$ respectively are the radial, circumferential and axial stress of casing thread; $\sigma_s$ is the minimum yield strength of the casing material.

(2) Maximum contact pressure criterion

The sealing performance of the thread is directly proportional to the maximum contact pressure of the sealing surface. When the contact pressure $p$ on the thread sealing surface is greater than the fluid pressure $p_0$ in the pipe to be sealed, the thread is considered not to leak.

$$p \geq p_0$$

### 3. Results and analysis

In this paper, the finite element method is used to analyze the Misses stress and contact pressure distribution of the HTRSS thread of casing with the coupling outer diameter 244.5mm under the condition of steam injection temperature of $T = 300$ ℃, steam injection pressure of $P = 12$MPa and axial tensile load of the casing of 600kN. The taper angle of the conical surface of the HTRSS thread is 1/12, and the shoulder angle is 10°, as shown in Figure 5.
3.1. Misses stress

The Misses stress of the HTRSS thread of casing is shown in Figure 6. The maximum Misses stress is 409.9MPa, which is less than the yield limit of the casing material, indicating that the HTRSS thread will not appear plastic failure. The maximum miss’s stress appears near the shoulder surface, which indicates that the shoulder is the most dangerous part. The main reason is that the large axial force will be produced under the effect of the thread tightening up, and a large extrusion pressure is formed between the shoulder surfaces. Therefore, excessive internal stress should be avoided in this part as far as possible when design the thread. The miss’s stress on the thread is far less than that on the shoulder surface, which means that the shoulder surface shares the axial force on the thread, and the shoulder surface plays an important role in protecting the thread from plastic failure under the action of excessive axial force. The Misses stress at both ends of the thread is higher than that at the middle of the thread, which means that the teeth at both ends of the thread bear more axial load and are more likely to fail. The maximum Misses stress in the threaded teeth occurs at the root of the teeth, so the failure form of the threaded teeth is mainly the root tear.

![Figure 6. Misses stress distribution of the HTRSS thread](image)

3.2. Contact pressure

The contact pressure of the HTRSS thread is shown in Figure 7. The maximum contact pressure is 425.7mpa, which is higher than the steam pressure in the pipe of 9MPa, indicating that the HTRSS thread will not appear sealing failure, resulting in steam leakage. The maximum contact pressure appears on the conical surface, indicating that the conical surface plays a major role in sealing.

The average contact pressure of the shoulder surface is slightly smaller than that of the conical surface and greater than that of the thread tooth surface, which indicates that the shoulder surface plays an auxiliary sealing role. Compared with the Misses stress near the conical surface and the shoulder surface, it can be seen that the conical surface has lower Misses stress but greater contact pressure than that of the shoulder surface, indicating that increasing the contact pressure of the conical surface is a safer way to improve the thread sealing performance. The contact pressure of the thread tooth surface is small, which plays a certain role in sealing. The contact pressure of the tooth surface mainly appears on the tooth top surface and the bearing surface. The contact pressure of the bearing surface is mainly produced by the axial extrusion between the male and female threads, which is produced by the pretightening operation. The contact force of the tooth top surface is mainly produced by the internal pressure of the casing and the thermal deformation of the casing. The average contact pressure of bearing surface is higher than that of tooth top surface. It shows that the thread tightening up is the main way to form the thread teeth seal.
3.3. Effect of the conical surface taper on sealing performance

Under the same external load, the maximum contact pressure and the maximum Misses stress of the HTRSS thread with the shoulder angle of 10° and the taper of the conical surface of 1/12, 1/14, 1/16 and 1/18 respectively are calculated by the finite element method. The influence of the taper of the conical surface on the sealing performance of the thread is analyzed.

As shown in Figure 8, with the increase of the conical surface taper, the maximum contact pressure of the shoulder surface and the conical surface decreases. However, when the taper is 1/16, the maximum contact pressure of the conical surface is greater than that of other taper, and the maximum contact pressure of the shoulder surface is greater than that of the taper of 1/14 and 1/18 taper. With the increase of the conical surface taper, the maximum Mises stress near the shoulder surface remains unchanged except when the taper is 1/16. The maximum Mises stress near the conical surface increases slightly with the increase of the conical surface taper. When the taper is 1/16, the maximum Mises stress near the conical surface decreases. When the taper of the conical surface is 1/16, it can not only ensure the high contact pressure of the conical surface and the shoulder sealing surface, enhance the sealing performance of the thread, but also reduce the Mises stress near the conical surface and the shoulder surface, reducing the risk of plastic failure of the thread.

![Figure 7. Contact pressure distribution of the HTRSS thread](image)

![Figure 8. Influence of the conical surface taper on contact pressure and Misses stress](image)
3.4. **Influence of shoulder angle on sealing performance**

Under the same external load, the maximum contact pressure and the maximum Mises stress of the HTRSS thread with the conical surface taper 1/16 and the shoulder angle of 5°, 10°, 15° and 20° respectively are calculated by the finite element method. The influence of the shoulder angle on the sealing performance of the HTRSS thread is analyzed.

As shown in Figure 9, with the increase of shoulder angle, the maximum contact pressure on the shoulder surface tends to increase, and the maximum contact pressure on the conical surface tends to decrease. With the increase of the shoulder angle, the maximum Misses stress near the conical surface increases slightly, but the maximum Misses stress near the shoulder surface increases rapidly. It shows that the increase of the shoulder angle is beneficial to improve the sealing performance of the shoulder while weaken the sealing performance of the conical surface. The increase of shoulder surface angle will lead to the increase of the Misses stress near the shoulder surface and the conical surface, especially the influence on the Misses stress near the shoulder surface. Therefore, too large angle of the shoulder surface will weaken the ability of the HTRSS thread to resist yield failure and lead to bond failure of shoulder surface.

![Figure 9. Influence of shoulder angle on contact pressure and misses stress](image_url)

3.5. **Shoulder angle and conical surface taper optimization**

Taking the high contact pressure of the conical surface and the small Misses stress near the shoulder as the optimal conditions, the shoulder angle and the conical surface taper of the HTRSS thread were optimized. The contact pressure of the conical surface and the Misses stress near the shoulder surface of 9 kinds of HTRSS threads with the shoulder surface angle of 10°, 15°, 20° and the conical surface taper of 1/14, 1/16, 1/18 are calculated by the finite element method, and the results are shown in Table 2. Compared with the results in the table, it is preferred that the shoulder angle is 10° and the conical surface taper is 1/16. In this case, the maximum contact pressure of the conical surface is 442MPa, which is the maximum of all threads and the maximum Misses stress near the shoulder surface is 391MPa, which is the minimum of all threads. It shows that the HTRSS thread with shoulder angle of 10° and conical surface taper of 1/16 has good sealing performance and strength performance for resisting yield failure.
Table 2. Maximum contact pressure and Misses stress of different conical surface taper and shoulder angle

| Shoulder angle | 1/14 | 1/16 | 1/18 |
|---------------|------|------|------|
| 10°           | 422(520) | 442(391) | 381(415) |
| 15°           | 397(608) | 395(490) | 376(614) |
| 20°           | 382(648) | 391(611) | 420(627) |

3.6. Comparative evaluation of sealing performance

Under the same external load condition, the finite element method is used to calculate the contact pressure and Misses stress of the HTRSS thread with shoulder angle of 10°, conical surface taper of 1/16, and the API trapezoid thread. The sealing performance of the two kinds of threads is compared and evaluated. The results are shown in Figure 10. The contact pressure of API trapezoidal thread mainly appears on the tooth top surface and bearing surface of the thread teeth. There is a gap between the tooth guide surfaces. It shows that the tooth top surface and bearing surface of thread teeth are the main sealing surfaces of the API trapezoidal thread, and there is a risk of leakage on the guide surface of teeth. Contact pressure is produced on the thread teeth, conical surface and shoulder surface of the HTRSS thread. The contact pressure of the conical surface and the shoulder surface is higher than that of the teeth surface, which indicates that in the HTRSS thread, the conical surface and the shoulder surface replace the teeth surface to become the main sealing surface. The maximum contact pressure of the HTRSS thread is 442.5MPa, which is much higher than that of the API trapezoidal thread, indicating that the sealing performance of the HTRSS thread is better than that of the API trapezoidal thread.

Figure 10. Contact pressure of the API trapezoidal thread and the HTRSS thread

4. Field application

The HTRSS thread designed in this paper has been applied in the Zhong18, Zhong32, BaiZhong7, HongQian1 region of Xinjiang Oilfield. The average casing damage rate of these region is reduced from 20% before to 8% after using the HTRSS thread.
5. Conclusion

(1) On the basis of API trapezoid thread structure, the conical surface and shoulder surface sealing structure are added on the HTRSS thread, which plays the main sealing role and enhances the sealing performance on the basis of ensuring the thread connection strength.

(2) With the increase of the conical surface taper, the sealing performance of the HTRSS thread tends to decrease. With the increase of the shoulder angle, the sealing performance of the shoulder surface is improved, while the sealing performance of the conical surface of the HTRSS thread is slightly reduced. The larger the shoulder angle is, the greater the Misses stress of the shoulder surface is, and the lower the yield resistance is. When the shoulder surface angle is 10° and the conical surface taper is 1/16, the HTRSS thread not only has good sealing performance, but also has good strength performance of resisting yield failure.

(3) The HTRSS thread has been widely used in heavy oil thermal recovery wells in Xinjiang Oilfield. The casing damage rate of application region has been reduced from 20% to 8%, which verifies the excellent sealing performance of the HTRSS thread.

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