Studied on Thermal Coupling and Sealing Characteristics of the Subsea Wellhead Connector Metal Seal

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Abstract. The sealing between subsea trees and high pressure wellhead is achieved by the metal seal inside the subsea wellhead connector. In this paper, the sealing performance of the metal seal under the dual role of load and temperature is analyzed. The theoretical analysis of the heat conduction in the sealing part of the subsea wellhead connector is carried out, and the basic equation of heat transfer for transient heat conduction is established, finite element simulation calculations were carried out to obtain the thermal stress of subsea wellhead sealing parts in the process of preload and operating. The results show that as the internal pressure of the subsea wellhead increases, the equivalent contact stress inside the metal seal gradually decreases, and the equivalent stress on the sealing surface is still greater than the initial sealing pressure, ensuring the sealing effect. As the internal pressure of the wellhead increases, the contact stress on the sealing surface of the metal seal increases gradually, with the increases of the temperature, the contact stress increases continuously, when the temperature is too high, the negative impact on the seal is relatively large, resulting in excessive stress inside the seal, which is prone to seal crushing accidents. The temperature effects can be reduced by appropriately reducing the amount of axial preload compression to avoid the metal seal failure.

1. Introduction
The subsea production system is an important facility for deep water oil and gas exploration. It is mainly composed of subsea tree, subsea wellhead, subsea manifold, subsea wellhead connector, subsea pipeline, etc [1, 2]. The common subsea production system is shown in Figure 1. The subsea wellhead connector is the key equipment for subsea well control connection. It is mainly installed in the bottom of the subsea blowout preventer and the subsea tree, and is used for quick connection between subsea tree and subsea wellhead, subsea blowout preventer and subsea wellhead [3]. The subsea wellhead connector creates a pressure barrier between the subsea well control equipment to prevent oil and gas leakage.

Fig. 1 Subsea Production System
The subsea wellhead connector and its metal seal ring are shown in Fig. 2. Its mainly consisted of an outer body, a driving piston, an action ring, a metal seal ring, and a lock block [4]. The left half is locked and the right half is unlocked. When the wellhead connector is locked, high-pressure hydraulic oil is injected into the closed locking hydraulic chamber, and the driving component pushes the piston to move axially, and the piston pushes the lock block to move radially. Tighten the metal seal, compress the seal gap, and provide sufficient axial preloading force to the seal to achieve the seal of the metal seal. During work, due to the effect of oil and gas pressure, the tree body and the connector tend to rise. At this time, the self-locking function of the locking mechanism works, and the connector can be locked and sealed without additional hydraulic pressure. Unlocking is the reverse process of the locking operation, and high pressure hydraulic oil can be injected into the unlocking hydraulic chamber.

![Subsea wellhead connector and metal seal ring](image)

Fig. 2 Subsea wellhead connector and metal seal ring

The core problem of the subsea wellhead connector is to solve the sealing problem of two docking objects. Because of the long-term bearing of the internal high-pressure medium and the external high-pressure seawater, the sealing form of the subsea connector is metal sealed. The metal butt presses the metal seal ring located in the middle to achieve sealing, that is, metal-to-metal contact sealing. The metal seal is out of the scope of The ASME Boiler and Pressure Vessel Code VIII-2 [5]. Wang [6] studied the optimum design of a mechanical connector for a subsea pipeline, and the structure was optimized with the zero-order method. Li [7] provided a theoretical calculation method for designing the metal seal ring of the subsea wellhead connector. Yun [8] studied the sealing contact characteristics of subsea collet connectors based on the theory of Hertz. Tang [9] investigated the sealing principle and the influence of temperature on the sealing performance of marine unbonded flexible pipes based on hydraulic-thermal finite element modeling. Carpenter [10] proposed a new advanced design concept for the high-pressure wellhead connector. Gawande [11], Haruyama et al. [12], Beghini et al. [13] all studied the sealing performance of the metal sealing gasket from the perspective of the leakage rate. Zhang et al. [14] used the contact theory to study the metal seal in the lenticular gasket of the subsea manifold connector. Sawa et al. [15] analyzed the influence of different flange thickness on the sealing performance of box-shape flange. Nelson and Prasad [16] formulated the bolt preload required for the safe operation of twin gasket joints. The majority of studies conducted in the past focused on the relationship between the bolt load and both the contact stress and the contact width using the finite element method, but little research on the thermal-mechanical coupling of subsea wellhead connectors. This paper focuses on the analysis of the thermal-mechanical coupling of the metal seal ring of the subsea wellhead connector under 50 ℃ to 120 ℃.

2. Thermal-mechanical coupling theoretical analysis of metal seals for subsea wellhead connectors

Under normal working conditions, the average external temperature of the subsea connector is 4 ℃, and the internal oil temperature is 70 ℃. Due to the effects of retentate and high-temperature steam injected by the workover, the maximum internal temperature of the subsea connector can reach 120 ℃. The metal seal ring inside the connector at the high-pressure wellhead not only bears the
weight of the subsea tree and the preloading force, which is to achieve the sealing effect. It is also affected by the internal high temperature liquid, which will cause its own temperature to change and generate thermal stress, which will affect the sealing effect. Therefore, when the subsea connector is working normally, the temperature field and the stress field are coupled to each other. Firstly, based on the principle of energy conservation, a thermodynamically coupled energy conservation equation is established. Then, based on this energy conservation equation, a finite element equation corresponding to the transient temperature field and thermal stress strain analysis of the structure is established.

With continuous media as the research object, V is the volume, S is the boundary, and ρ is the density. According to the principle of energy conservation, the following expressions can be derived:

\[
\int V \rho \frac{\partial V_i}{\partial t} dV + \int U \frac{\partial \rho}{\partial t} dV = \int \rho \left( b_i V_i + \bar{Q} \right) dV + \int (P_i V_i - H) dS
\]  

(1)

In the formula, \( V_i \) is the velocity field; \( U \) is the internal energy of the medium; \( \bar{Q} \) and \( b_i \) are the volumetric heat flow and volume force respectively; \( P_i \) is the boundary pressure; \( H \) is the heat flow intensity per unit area on the boundary.

Based on the principle of conservation of momentum, a force equilibrium equation in the form of a medium integral is established:

\[
\int V \rho \frac{\partial V_i}{\partial t} dV = \int P_i dS
\]  

(2)

Then introduce Cauchy stress component \( \sigma_{ij} \) and use Cauchy stress to represent the pressure on the boundary:

\[
p_j = n_i \sigma_{ij}
\]  

(3)

In the formula, \( n_i \) represents the unit normal direction on the boundary.

Substituting the Force balance equation in integral form (2) into the energy conservation equation (1), the energy conservation equation for the thermo-mechanical coupling is obtained:

\[
\int \left( \rho \left( \frac{\partial U}{\partial t} - \frac{\partial U}{\partial t} \right) + \sigma_{ij} \frac{\partial V_j}{\partial x_i} \right) dV = \int H dS
\]  

(4)

In continuous media, the relationship between the element displacement vector \( U \) and the node displacement vector \( u \) is as follows:

\[
U(x, t) = N(x)u(t)
\]  

(5)

Among them, \( x \) represents the coordinate value; \( t \) represents the time variable; \( N(x) \) is the shape function matrix.

(5) Differentiate the time variable to obtain the relationship of strain rate:

\[
V(x, t) = N(x)\dot{u}(t)
\]  

(6)

Similarly, the temperature field in the medium can be expressed as:

\[
T_n(x, t) = T(t)B(x)
\]  

(7)

In the formula, \( T(t) \) represents the temperature vector value of the medium node, and \( B(x) \) represents the interpolation function of the temperature field. Then the strain matrix can be represented by the difference function of the temperature field and the displacement vector of the node:

\[
\varepsilon(x, t) = LU(x, t) = B(x)u(t)
\]  

(8)
Among them, \( L \) stands for differential operator.

From the formulas (5) to (8), the finite element equations corresponding to the transient temperature field and thermal stress strain field of the structure can be deduced as:

\[
\ddot{u}^T[K_u \ddot{u}(t) + M_T \dot{T}(t) - F(t)] = 0
\]

\[
T^T[C_u \dot{T}(t) + M_u \ddot{u}(t) - D - Q - K_T T(t)] = 0
\]

In the formula, \( K_u \), \( C_u \) and \( M_u \) represent mechanical stiffness matrix, heat capacity matrix and thermo-mechanical coupling matrix respectively; \( M_T \) and \( K_T \) represent heat conduction matrix and thermal stiffness matrix respectively; \( F \) represents load vector; \( Q \) and \( D \) represent thermal load vector and dissipation Vector. After combining (9) and (10), we can get the comprehensive matrix equation:

\[
[K_u \quad M_T \quad M_u \quad C_u] \begin{bmatrix} \ddot{u}(t) \\ \dot{T}(t) \end{bmatrix} = \begin{bmatrix} F(t) \\ P(t) \end{bmatrix}
\]

In the formula, \( P(t) = K_T T(t) + Q + D \).

For the problem of heat generation due to contact friction, the relationship between the work of friction between the two contact surfaces and the surface heat flow can be expressed as:

\[
Q_{fr} = MF_{fr} V_r
\]

In the formula, \( M \) is the work-heat conversion coefficient; \( F_{fr} \) is the friction force of the contact surface; \( V_r \) is the relative sliding speed of the surface.

3. Thermal-mechanical coupling FEA of metal seals for subsea wellhead connectors

The 18-3/4 inch subsea wellhead connector metal seal of an oilfield in the South China Sea was used as an example, with a design pressure of 69 MPa. As shown in Figure 3, the numerical model was established using the finite element method. The axisymmetric model of the subsea wellhead connector was established with ANSYS 18.0 software. The displacement load was applied to the upper and lower contact faces of the metal seal ring, causing pressure from above and below, respectively. Therefore, the internal pressure and temperature was applied during operating conditions. The calculation results of the contact stress and preload compression on the sealing surface of the metal seal ring was analyzed. The metal sealing ring material is 316L austenitic stainless steel. The density of this material is 7800 kg/m\(^3\), Poisson's ratio is 0.31, and the yield strength is 287 MPa. The main material of the tree body, the wellhead and the wellhead connector is alloy steel 8630. The density is 7750 kg/m\(^3\), the Poisson's ratio is 0.33, and the yield strength is 550 MPa. In the subsequent finite element analysis, all components are assumed to be linear elastic materials. The main parameters of the metal seal ring are shown in Table 1.

| Parameter | Value |
|-----------|-------|
| The seal ring diameter \( D \) | 523.82 mm |
| The seal ring height \( h \) | 101.6 mm |
| The seal ring cross-sectional area \( F_R \) | 2892.96 mm\(^2\) |
| The seal ring elastic modulus \( E_R \) | 1.95\times10^5 MPa |
3.1 Finite element analysis of the metal seal

3.1.1 Finite element analysis of the metal seal under preload conditions
In the preload conditions, different radial compression amounts determine the stress distribution on the sealing surface of the metal seal, which directly affects the sealing performance of the seal. In reality, the radial compression is achieved by the hydraulic locking device inside the connector driving the axial displacement of the tree part to squeeze the seal. Due to the declination difference between the sealing cone and the sealing cone on the tree, the initial contact point on the outermost side of the sealing surface is used as the starting point of the study. Take the six displacements are 0.5mm and 1.0mm, 1.5mm, 2.0mm, 2.3mm, 2.5mm as the research object. The finite element software was used to analyze the equivalent stress on the sealing cone surface of the metal seal ring to obtain the maximum, minimum and average equivalent stress on the sealing surface. The results at the 6 special points are shown in Table 2.

According to GB 150, the specific pressure \( y \) of the gasket suitable for sealing the wellhead is 179.5MPa. From the analysis results, when the displacement is 2mm, only a few nodes have a stress value of 287MPa, which does not constitute an effective seal. According to the linear analysis results, it was found that when the displacement was 2.3 mm, the equivalent stress of the Mises of most of the sealing surface nodes exceeded the yield strength of the metal seal material, and the average stress was 314 MPa. This shows that a large area of plastic yielding occurred on the sealing cone surface, and an effective seal was formed.

| Axial displacement /mm | 0.5  | 1.0  | 1.5  | 2.0  | 2.3  | 2.5  |
|------------------------|------|------|------|------|------|------|
| Maximum equivalent stress /MPa | 131  | 174  | 229  | 297  | 347  | 371  |
| Minimum equivalent stress /MPa | 61   | 126  | 192  | 260  | 302  | 331  |
| Average equivalent stress /MPa | 72   | 152  | 208  | 274  | 314  | 341  |

Table 2 Equivalent stress of the metal seal ring under different axial displacement

Figure 4 shows the contact stress on the sealing surface in the preload state. The contact stress increases with the increase of the axial preload compression. When the axial pre-load compression is 2.3 mm, the finite element value of the contact stress meets Requirements for the preload seal specific pressure criterion. When the axial preload compression increases to about 2 mm, the increase in the calculated value of the finite element slows down. This is because the contact width on the sealing surface gradually increases, resulting in a trend of slower increase in contact stress.
3.1.2 Finite element analysis of the metal seal under operating conditions
Under operating conditions, the internal pressure of oil and gas acts on the inside of the metal seal ring, the tree body, and the wellhead wall. Figure 5 shows the relationship between contact stress, sealing specific pressure, and internal pressure on the sealing surface of the metal seal ring in the operating state. As can be seen from the figure, the contact stress is always greater than the sealing specific pressure, which ensures the sealing effect. At the initial stage of the increasing the operating internal pressure, the operating contact stress of the sealing cone has a process of first decreasing and then increasing. When the axial force generated by the internal pressure cancels the axial preload force during preloading, the contact stress on the sealing surface reaches a minimum. After that, the internal pressure continued to rise, and the contact stress on the sealing surface continued to increase.

3.2 Thermal-mechanical coupling finite element analysis of the metal seal
Based on the theory of thermo-mechanical coupling analysis, the thermo-mechanical coupling finite element analysis and calculation of metal seals are performed. Coupled with the temperature field, the temperature of the internal medium is taken as the research object at the special points of 50 °C, 70 °C, 90 °C and 120 °C, and the influence of thermal stress on the stress distribution of the metal seal ring is analyzed.

The calculation results of the produced fluid inside the wellhead at different temperatures are analyzed. The measured values of the temperature are shown in Table 3. When the temperature of the
produced fluid at the wellhead is 50 °C, the surface node temperature of the inner side of the seal that directly contacts the produced fluid is all reached 50 °C, and the lowest node temperature of the sealing cone was 10.35 °C. The temperature gradually decreases from the inside to the outside, with a maximum temperature difference of 39.65 °C and a radial temperature gradient of 1.32 °C/mm. The higher the temperature of the wellhead produced fluid, the greater the temperature gradient inside the seal.

Table 3 Temperature detection values of the metal seal

| Internal medium temperature /°C | Maximum temperature of the sealing surface /°C | Minimum temperature of the sealing surface /°C | Radial temperature gradient °C/mm |
|---------------------------------|-----------------------------------------------|-----------------------------------------------|-----------------------------------|
| 50                              | 50                                            | 10.35                                         | 1.32                              |
| 70                              | 70                                            | 11.98                                         | 1.93                              |
| 90                              | 90                                            | 16.39                                         | 2.45                              |

Figure 6 shows the relationship between contact stress and axial preload compression at different wellhead produced fluid temperatures. It can be seen from Fig. 6 that the contact stress increases with the increase of the axial preload compression, under the same axial preload compression, the contact stress of the metal seal increases with the increase of temperature.

![Fig. 6 Contact stress of sealing surface at different temperatures](image)

From the results in Table 4, it can be seen that as the temperature of the wellhead produced fluid continues to increase, the axial preload compression decreases when the equivalent stress on the sealing surface reaches 287MPa. Compared with the compression amount of 2.3mm when the temperature is not considered, the percentage difference increases with increasing temperature. At a normal wellhead temperature of 70 °C, the percentage difference is 8.7%, and under special circumstances, such as the high temperature for workover injection, the maximum internal temperature of the tree reached 120 °C, compared with the axial preload compression without considering the temperature, the difference was 21.7%. This shows that when the wellhead temperature is too high, the negative impact on the seal is relatively large, which causes the stress inside the seal to be too high, and the seal collapse accident is prone to occur. Therefore, in the actual production process, try to avoid accidents with excessive temperature, otherwise it will cause serious damage to the seal structure, which may cause leakage accidents.

Table 4 Comparison of axial preload compression under temperature effects

| Temperature /°C | Axial preload compression /mm | Relative percentage without considering temperature |
|-----------------|-------------------------------|-----------------------------------------------------|
| 50              | 2.2                           | 4.3%                                                |
| 70              | 2.1                           | 8.7%                                                |
| 90              | 1.9                           | 17.4%                                               |
| 120             | 1.8                           | 21.7%                                               |
Fig. 7 is a comparison diagram of the contact stress of the sealing surface. It can be seen from the figure that compared with the contact stress on the sealing surface when there is no temperature field, the contact stress distribution on the sealing surface is basically the same when the temperature of the wellhead produced fluid is 50 ℃, 70 ℃, 90 ℃, and 120 ℃, respectively. The higher the temperature, the greater the contact stress. When the temperature is higher than 90 ℃, the contact stress on the sealing surface increases greatly, and it exceeds 3 times the yield strength of the seal, which greatly shortens the service life of the seal ring. In severe cases, the seal may be crushed, causing seal failure.

![Fig. 7 Comparison of sealing surface contact stress under different temperature](image)

4. Conclusion

(1) This paper analyzes the thermo-mechanical coupling problem of the metal seal of the subsea wellhead connector by the finite element method, established the energy conservation equation, and derived the finite element equations for the stress field and transient temperature field.

(2) The finite element analysis software was used to simulate the sealing performance. When the axial preload compression was 2.3mm, the average contact stress of the sealing surface was 314MPa, which met the requirements of the preload seal. When the axial force generated by the internal pressure cancels the axial preload force during preloading, the contact stress on the sealing surface reaches a minimum. After that, the internal pressure continued to rise, and the contact stress on the sealing surface continued to increase.

(3) Thermal-mechanical coupling analysis results show when the equivalent stress on the sealing surface reaches 287MPa, compared with the compression amount of 2.3mm when the temperature is not considered, the percentage difference increases with increasing temperature. At a temperature of 70 ℃, the percentage difference is 8.7%. At a temperature of 120 ℃, compared with the axial preload compression without considering the temperature, the difference was 21.7%. This shows that when the wellhead temperature is too high, the negative impact on the seal ring is relatively large, resulting in excessive stress inside the seal ring, which is prone to the collapse of the seal ring. In order to ensure the sealing performance of the subsea wellhead connector, the sealing ring can be protected by appropriately reducing the amount of axial preloading compression.

5. References

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