Analysis on Sealing Mechanism of Casing Connection

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Abstract. This article describes the sealing mechanism of API casing thread connection and premium casing thread connection, and determines that the main macro factors affecting the sealing performance of premium thread connection are surface quality, contact pressure and contact width of sealing surface. The influence law of these three factors on sealing performance is discussed. The analysis results in this paper can provide the theoretical ground for improving the sealing performance of premium thread connection.

1. Introduction
With the expansion of oil and gas exploration and development areas in the world, the increasingly harsh drilling environment, and the continuous improvement of cementing and completion quality requirements, the sealing performance of API casing thread connection has been difficult to meet the technical requirements of oilfield application [1]. Therefore, some advanced oil well pipe manufacturers have developed some premium casing thread connections. Premium casing thread connection, namely non API threaded connection, is a kind of product with high technical content, high added value, difficult processing, strict quality requirements, strong theory and practice, especially suitable for gas wells, ultra-deep wells, high pressure wells, thermal recovery wells, directional wells and other demanding working conditions. It is an advanced stage of the development of oil well pipe production technology [2].

Compared with the API connection, better sealing performance is a design goal of premium casing thread connection [3]. Before the development of premium casing thread connection, the sealing mechanism of traditional API casing connection and premium casing connection should be analyzed first. Only in this way can the sealing design of premium casing thread connection be carried out according to the defects and deficiencies of traditional API casing connection.

2. Sealing mechanism of API casing thread connection
API standard thread has an inevitable space spiral leakage channel. In essence, this structure of API thread does not have the ability of fluid sealing. In order to make it have certain fluid sealing ability, some sealing measures must be taken.

The sealing method adopted by the API thread connection is packing sealing, which uses some fillers to block the leakage channel to achieve a certain ability to seal the fluid [4]. The most common filler is thread compound. Under the extrusion of thread contact pressure, the soft metal filler in the thread compound will form solid particles, which will agglomerate and block the leakage channel between the threads, thus playing a sealing role. In addition to thread compound, API casing thread connection also
need surface treatment. Generally, phosphorus plating is adopted. This kind of soft coating can also fill the thread gap after the thread is buckled.

Although API thread is sealed with thread compound, it has a certain sealing ability in the early stage of buckle. However, due to the fact that the thread compound belongs to oil matrix grease, under the condition of high temperature or long-term service, the thread compound is continuously dried, volatilized and gradually deteriorated, resulting in significant decline in the sealing performance of the thread. Some studies have shown that API thread connection will leak in long-term use due to the gradual failure of thread compound [5]. The sealing capacity of thread compound is also limited, so API threaded connection can only be used in conventional oil wells, and cannot be used safely in oil and gas wells with slightly higher pressure.

3. Sealing mechanism of premium casing thread connection

For gas wells with high pressure, premium casing thread connection with better sealing performance must be selected. The sealing function of premium casing thread connection is no longer realized by threaded part, but a special sealing structure is additionally added. This special sealing structure usually adopts metal/metal sealing structure. This structure changes the non-contact seal of API thread connection to contact seal, which is one of the reasons for its better sealing performance.

The metal/metal seal mainly depends on the interference fit between the two contact surfaces to obtain a higher contact pressure to achieve the seal. In fact, the metal is affected by processing factors, the two sealing contact surfaces cannot be completely smooth. After the fit, there is still a slight gap between the two sealed contact surfaces. According to fluid mechanics, when the fluid moves in a small sealing gap, the sealing performance of the fluid is related to the flow state and flow resistance. For gas medium, the flow state can be described by Knudsen number $Kn$. When $Kn$ is greater than 1, the flow state is molecular flow, when $Kn$ is less than 0.01, the flow state is viscous flow, when $Kn$ is between 0.01 and 1, the flow state is a transitional flow between molecular flow and viscous flow. As shown in formula (1)

$$Kn = \frac{2\lambda_d}{d}$$  \hspace{1cm} (1) 

In the formula, $\lambda_d$ is the average free path of the gas molecules, $d$ is the equivalent diameter of the leak channel, $\lambda_d$ can be obtained by formula (2), $d$ can be obtained by formula (3).

$$\lambda_d = \frac{kT}{\sqrt{2\pi d_a^2 p}}$$  \hspace{1cm} (2) 

In the formula, $k$ is Boltzmann's constant, $T$ is temperature, $d_a$ is the effective diameter of the molecule, $p$ is the medium pressure.

$$d = \frac{4A}{H}$$  \hspace{1cm} (3) 

In the formula, $A$ is the cross-sectional area of the leak channel, $H$ is the wet circumference of the leak channel.

The movement of the medium between the small gaps of the main sealing structure of the premium casing thread connection is simplified as the axial steady flow of the fluid between the annular gap models of two coaxial long straight circular pipes. The model is shown in Fig. 1, and the equations (4) and (5) can be obtained.
In the formula, \( h \) is the height of the annular gap, \( R \) is the radial dimension of the main seal contact surface relative to the central axis of the joint, assuming that \( R \) is a certain value.

![Figure 1. The annular gap model of two coaxial long straight circular tube.](image)

 Bring Equation (4) and Equation (5) into Equation (3) to get Equation (6).

\[
A = \pi(R + h)^2 - \pi R^2 \quad (4)
\]

\[
H = 2\pi R + 2\pi(R + h) \quad (5)
\]

In the formula, \( h \) is the height of the annular gap, \( R \) is the radial dimension of the main seal contact surface relative to the central axis of the joint, assuming that \( R \) is a certain value.

Bring Equation (4) and Equation (5) into Equation (3) to get Equation (6).

\[
d = 2h \quad (6)
\]

Bring Equation (6) into Equation (1) to get Equation (7).

\[
Kn = \frac{\lambda_a}{h} \quad (7)
\]

When the medium pressure is constant and the temperature is constant, \( \lambda_a \) is a constant. It can be seen that the value of \( Kn \) at this time depends only on the height \( h \) of the leak channel.

When two sealing surfaces contact, due to the uneven micro surface, they must be divided into contact part and non-contact part. When a premium casing thread connection is subjected to a small internal pressure, such as 0.1MPa, the small gap height \( h \) of the contacted part is very small. At this time, \( Kn \) is greater than 1, and the flow characteristic is molecular flow. The value of \( h \) at the non-contact part will be between hundreds of nanometers and thousands of nanometers, and the flow characteristic at this time is mainly a transitional flow. When a premium connection is subjected to a large internal pressure, such as 60MPa, since the size of the leak channel cannot be smaller than the diameter of the gas molecule, \( Kn \) must be less than 1, the flow characteristic is mainly viscous flow.

For the molecular flow form, according to hydrodynamics, the leakage rate of the molecular flow in the leakage channel, that is, the flow rate \( Q \), can be obtained by equation (8).

\[
Q = \frac{4}{3} \int_0^L \frac{H}{A^2} v_a \Delta p dL \quad (8)
\]
In the formula, $L$ is the length of the leak channel, $\Delta p$ is the pressure difference across the leak channel, $v_a$ is the average velocity of the gas molecules and it can be calculated by formula (9).

$$v_a = \sqrt[8]{\frac{8\rho T}{\pi M}}$$ (9)

In the formula, $\rho$ is a constant, $T$ is the temperature, $M$ is the molar mass of the gas. When the temperature is constant, $v_a$ is a constant. Bring equation (4) and equation (5) into equation (8) to get the molecular flow rate $Q$ in the model.

$$Q = \frac{2\pi v_a \Delta p}{3L} (2R + h)^2 h$$ (10)

The form of viscous flow is divided into laminar flow and turbulent flow, which can be determined by Reynolds number $Re$. Aiming at the annular gap-shaped leakage channel model of the main sealing structure of premium casing thread connection, $Re$ can be obtained from equation (11).

$$Re = \frac{uA}{vH}$$ (11)

In the formula, $v$ is the kinematic viscosity of the medium, $u$ is the average flow rate of the fluid, $uA$ can be approximated as the leakage of a special threaded joint per unit time. API RP 5C5 stipulates that the judgment condition for the connection not to leak is that the leakage volume is less than 0.9cm$^3$ within 15min. Assuming that $uA$ is equal to 1mm$^3$/s, it can be obtained through calculation and analysis that the form of viscous flow between the small gaps of the main sealing structure of the special threaded joint should be laminar flow.

For the form of laminar flow, according to the Hage-Poiseuille law of hydrodynamics, the axially steady laminar flow rate $Q$ of the viscous fluid between the annular gaps of two coaxial circular tubes can be obtained by equation (12).

$$Q = \frac{\pi \Delta \rho h (h + 2R)}{4\eta L} \left[ 3h^2 + 6hR + 6R^2 - \frac{(2R + h)h}{\ln(R + h) - \ln R} \right]$$ (12)

In the formula, $\eta$ is the dynamic viscosity of the fluid medium, this value is a constant.

Assuming that the pressure difference $\Delta p$ is always the same, it can be seen from equations (10) and (12) that, whether in the form of molecular flow or laminar flow, the leakage rate $Q$ is only related to the height $h$ and the length $L$ of the leakage channel. Because the leakage channel is caused by the unevenness of the sealing surface, and the sealing surface is usually processed by precision turning or grinding, the value of $h$ is not greater than $10^{-3}$mm. Within this range, the greater the leak channel height, the greater the leak rate, and the greater the leak length, the smaller the leak rate.

However, the leakage channel under the microscopic level is actually not an ideal long straight channel, and the height of the leakage channel is irregularly changed. In addition to the influence of contact pressure and surface processing accuracy, the real leakage rate is usually difficult to be calculated in the process of product design. Therefore, in the sealing design of special threaded joints, the factors $h$ and $L$ that affect the leakage rate can be used as indicators to measure the sealing performance of the product.
The leak channel height \( h \) and the leak length \( L \) are macroscopically expressed as the obstruction of the leak channel to the fluid flow. The factor \( L \) of the main sealing structure of a special threaded joint is mainly affected by the contact width of the two sealing contact surfaces. The larger the contact width, the greater the value of the factor \( L \). The factor \( h \) of the leakage channel is mainly affected by the contact pressure of the sealing surface. The greater the contact pressure of the sealing surface, the smaller the value of the factor \( h \) of the leakage channel. In addition, the factor \( h \) is also affected by the true geometry of the surfaces of the two sealing contact surfaces. The smaller the surface roughness, the smaller the surface waviness, and the smaller the surface shape error, the smaller the factor \( h \). Therefore, the contact width is usually used as a parameter to measure \( L \), and the contact pressure and surface processing accuracy are used as parameters to measure \( h \), as shown in Figure 2.

![Figure 2.](image)

Figure 2. Relationship diagram of tightness and influencing factors.

Based on this mechanism, the design principle of the metal/metal seal should be: the greater the contact width of the sealing surface, the greater the contact pressure, and the higher the surface processing accuracy, the better the sealability of this structure. However, there is no direct relationship between the factor \( L \) and the contact width of sealing surface at macro level. In the same macroscopic contact width, the micro channel length may vary greatly due to the different contact states of the micro surface, so the leakage channel length cannot be measured simply by the contact width of the sealing surface. Moreover, when the external load is constant, the contact pressure and contact width of the sealing surface are a pair of contradictory values. The increase of contact width will inevitably lead to the decrease of contact pressure per unit area. In this way, the increase of contact width will weaken the sealing performance from another aspect. This sealing mechanism needs further study.

From another perspective, it is difficult to ensure a high contact pressure on the entire sealing contact surface. The high-pressure area at the sealing contact surface is actually a narrow band-shaped area. Increasing the contact width of the sealing surface or the length of the leakage channel actually has little effect on the sealing effect, so it is also possible to adopt a line-contact seal design for the sealing contact surface. Some manufacturers have also developed some premium casing connections with line contact seal structures, such as the NK3SB series premium connection developed by NKK, and in actual use, it has also proved that this connection has good sealing performance [6].

Since the influence of the width of the contact surface on the leakage rate needs to be further studied, and considering the contradictory factors of contact pressure and contact width at the same time will make the evaluation of the sealing performance difficult, the author recommends that when designing the seal of premium connection, only the contact pressure and surface quality are used as factors to measure the sealing performance. The basis of sealing design of premium casing thread connection can be determined as follows: under the highest surface processing accuracy determined by considering processing and other factors, when the contact pressure of sealing contact surface is greater than the pressure inside the fluid, the structure has sealing ability, and the greater the contact pressure, the better the sealing performance.
4. Conclusion

The sealing performance of the premium casing connection is better than that of the API connection, and its sealing performance is mainly affected by the surface quality, the contact pressure and the contact width of the sealing surface. Generally, the better the surface quality and the higher the contact pressure, the smaller the height of the leakage channel and the better the sealing performance, the influence of the contact width of the sealing surface on the sealing performance needs to be further studied. In the sealing design of premium casing connection, we can take "under the highest possible surface machining accuracy, when the contact pressure of sealing contact surface is greater than the pressure inside the fluid, the structure has sealing ability, and the greater the contact pressure, the better the sealing performance" as the design basis.

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