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Structural Design of Connection Methods for Well Control Controller Tubing Hanger

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Abstract

This paper conducts a systematic design of the connection structure between the well control controller and the tubing hanger, focusing on in-depth analysis and strength verification of threaded connection methods. A comparison is made among four common connection forms—threaded, flanged, clamped, and welded connections—in terms of their characteristics and applicable conditions. The threaded connection scheme is finally selected. Detailed descriptions are given on the tooth-profile design, basic parameters, and tensile-strength calculation methods for both API buttress threads and triangular threads. In terms of structural design, a conical sealing-surface structure employing dual-step mating of internal and external threads is proposed to enhance the gas-tightness and torque resistance of the connection. Finite-element analysis is performed to verify the strength of the selected P110 steel API buttress thread joint, including the thread-tooth strength and the tubing-coupling tensile strength. The results show that under a given axial load of 200 kN, the ultimate load-bearing capacity of the thread teeth is 377.4 kN, and the tubing tensile strength is 0.63 MPa, both meeting the operational requirements, thereby validating the feasibility and safety of the designed connection structure. This study provides a theoretical basis and engineering reference for the selection and strength assessment of tubing-hanger connection methods in well-control equipment.

Keywords

Threaded Connection; API Buttress Thread; Strength Verification; Tubing-hanger Structural Design.

1. Introduction

The reliability of well control systems in oil and gas wells is directly related to the safety and productivity of drilling operations. The connection structure between the well control controller and the tubing hanger is one of the critical links, and its performance must comply with stringent industry standards and specifications [1]. The connection area must maintain structural integrity and sealing performance under high-pressure, high-temperature, and complex loading conditions. Failure could lead to serious well control risks, making the study of its failure mechanisms and improvement measures an important research topic [5]. Currently, commonly used connection methods in engineering include threaded connections, flange connections, clamp connections, and welding. Among these, threaded connections are widely adopted due to their compact structure, ease of installation and disassembly, and good load-bearing performance [2]. However, different thread types exhibit significant differences in load-bearing mechanisms, sealing characteristics, and failure resistance [4]. Their selection and design require comprehensive analysis and verification based on specific well conditions and mechanical environments [8].

This paper focuses on the design and analysis of the connection structure between the well control controller and the tubing hanger, with an emphasis on theoretical analysis and strength verification of threaded connection methods. Firstly, a systematic comparison of the characteristics and applicable scopes of different connection forms is conducted, leading to the selection of a threaded connection scheme. Secondly, the tooth profile parameters, tensile strength, and connection performance of API buttress threads and triangular threads are analyzed. The design basis for API buttress threads mainly references relevant standards and strength calculation formulas [1, 3, 10]. Building on this, a gas-tight threaded structure with dual-step sealing surfaces is proposed to enhance the sealing reliability of the joint under high-pressure environments [7]. Finally, finite element analysis is employed to verify the strength of the selected P110 steel API buttress thread joint [9], validating its safety and feasibility under actual axial loads. This work aims to provide theoretical foundations and engineering references for the design and application of connection structures in well control equipment.

2. Structural Design of Connection Methods

2.1. Connection Methods

In the design of the connection between the well control controller and the tubing hanger, four main methods are considered: threaded connection, flange connection, clamp connection, and welded connection. Among these, the threaded connection is selected as the final implementation scheme due to its simple structure, ease of installation and disassembly, and suitability for high-pressure environments. The design will adopt a tubing coupling structure with external threads on both ends to balance connection reliability and sealing performance. The other connection methods each have their applicable ranges depending on different pressure, temperature, and working conditions.

2.1.1. Threaded Connection

Threaded connection is a common type of detachable connection, widely used because of its simple structure and ease of installation and disassembly. Threaded connections can be categorized into four types: triangular threads, cylindrical pipe threads, rectangular threads, and trapezoidal threads. Special threaded joints often employ forms such as buttress threads, modified buttress threads, hook threads, and wedge threads to improve connection efficiency and anti-galling performance.

In threaded connections, common joint types include bolt connections, double-ended stud connections, screw connections, and set screw connections.

(1) Bolt Connection

Bolt connections offer advantages such as easy disassembly, reusability, and high connection strength. However, they require regular inspection and maintenance to ensure reliability and safety. When using bolt connections, it is necessary to select appropriate bolts and nuts based on factors such as the material, dimensions, and working environment of the connecting components, and to install and tighten them correctly according to specifications.

(2) Double-Ended Stud Connection

Double-ended stud connections provide high connection strength, simple structure, and ease of installation. However, suitable studs and nuts must be selected according to the material, dimensions, and working environment of the connecting components, and installation and tightening must be performed correctly as per specifications. When using double-ended stud connections, attention must be paid to the symmetry and parallelism of the stud heads to ensure uniform and stable connections.

(3) Screw Connection

Screw connections offer a simple structure and ease of installation but relatively lower connection strength. Suitable screws and nuts must be selected based on the material, dimensions, and working environment of the connecting components, and installation and

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tightening must be performed correctly as per specifications. When using screw connections, parameters such as screw length, diameter, thread type, and thread depth must be considered to ensure connection reliability and safety.

(4) Set Screw Connection

Set screw connections provide high connection strength, simple structure, and ease of installation. However, suitable set screws and nuts must be selected based on the material, dimensions, and working environment of the connecting components, and installation and tightening must be performed correctly as per specifications. When using set screw connections, control over the preload and tightening torque is essential to ensure reliability and safety. Additionally, regular inspection and maintenance of set screw connections are necessary to prevent issues such as loosening and fatigue failure.

2.1.2. Flange Connection Structure

The flange connection method is used to connect the well control controller to the tubing hanger. It can be divided into two forms: standard flange connection and sealed flange connection. Standard flange connections are suitable for low-pressure, low-temperature oil and gas wells, while sealed flange connections are suitable for high-pressure, high-temperature oil and gas wells.

2.1.3. Clamp Connection Structure

The clamp connection method is used to connect the well control controller to the tubing hanger. It can be divided into two forms: single clamp connection and double clamp connection. Single clamp connections are suitable for low-pressure, low-temperature oil and gas wells, while double clamp connections are suitable for high-pressure, high-temperature oil and gas wells.

2.1.4. Welded Connection Structure

The welded connection method is used to connect the well control controller to the tubing hanger. It can be divided into two forms: automatic welding and manual welding. Automatic welding is suitable for mass production, while manual welding is suitable for small-batch production and maintenance.

Based on specific operational requirements and downhole environmental conditions, the threaded connection method will be adopted to connect the well control controller to the tubing hanger. Considering the structural characteristics of both the tubing hanger and the well control controller, a tubing coupling with external threads on both ends will be used for the connection.

2.2. API Buttress Thread

2.2.1. API Buttress Thread Tooth Profile Design

The design and structure of the API buttress thread (abbreviated as BC) feature several characteristics, including a trapezoidal tooth profile, a slightly curved crest, a load flank angle of 3°, and a guide flank angle of 10°.

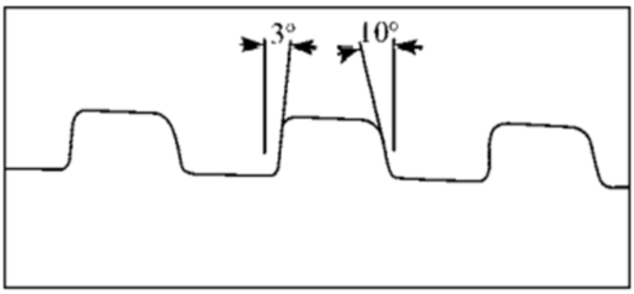

Fig 1. API Buttress Thread Tooth Profile

Furthermore, basic parameters and tensile strength design for the API buttress thread tooth profile are also specified. For casing with a size of 13 inches and below, the thread height is 0.062 in, the pitch is 0.200 in, and the taper is 1/16. For casing larger than 13 inches, the thread height and pitch remain 0.062 in and 0.200 in respectively, while the taper is 1/12. To enhance its tensile strength design, the API buttress thread casing joint has been optimized in terms of internal structure and external fit, ensuring its overall strength and tensile performance.

To improve the axial load-bearing capacity of tubing couplings, API Spec 5B adopts a "buttress" cross-sectional shape, known as the "equal strength beam." The new tooth profile angle is 13 degrees, consisting of a 10-degree guide flank half-angle and a 3-degree load flank half-angle (see Fig 1). To reduce the radial component force F induced by axial tensile loads, the load flank half-angle employs a small-angle self-locking design. This design ensures that the radial component force F on the load-bearing contact surfaces of the internal and external threads under load is less than the frictional force between the thread materials (i.e., the friction angle $\lambda = \arctan \mu$, where μ is the material's coefficient of friction). Consequently, the load flank half-angle α of the thread is less than or equal to the friction angle λ between the internal and external thread materials, reducing the likelihood of radial slip failure. This is also the primary reason why API buttress thread casing joints are less prone to slip failure under tensile loading.

2.2.2. Tensile Strength Design of API Buttress Thread Joint

The API buttress thread casing joint enhances its overall tensile strength through optimized structural dimension design. Specifically, the design must consider the following two aspects:

(1)The tubing coupling joint itself must possess sufficient tensile strength.

(2)The API buttress thread casing joint improves its overall tensile strength via optimized structural dimension design. Among these, the internal and external threads must have adequate engagement length to ensure sufficient contact area and thread shear area. The external thread extends naturally to the pipe outer diameter according to the specified taper to avoid abrupt run-out conditions. The coupling internal thread will mate with the external thread, enabling the tubing coupling thread joint under axial tensile loading to approximate the tubing coupling's cross-sectional area at the critical cross-section (see Fig 2).

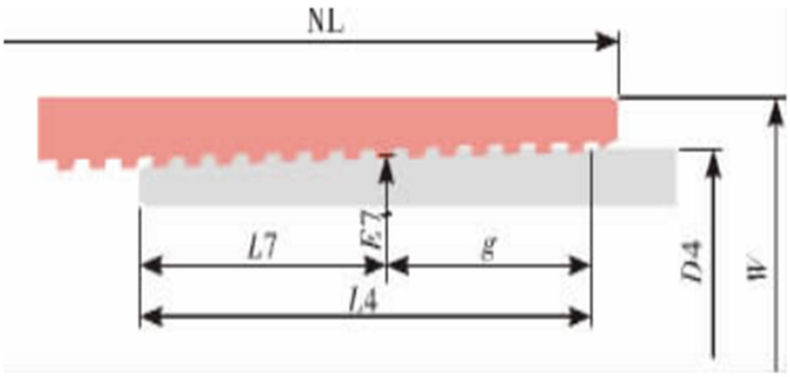

Fig 2. API Buttress Thread Structural Dimensions

2.2.3. API Thread Connection Strength

The calculation formulas for the casing connection strength of API-specified buttress thread joints are provided in API Bul 5C2, as shown in the following two equations. These calculation formulas were proposed based on the formulas in the report "Buttress Thread Connection Strength" by W.O. Clinedist. Derived from regression analysis of test results from 151 buttress thread joint casings with outer diameters ranging from 114.3 to 508.0 mm and steel grades from 276 to 1034 MPa, the casing connection strength of buttress thread joints depends on the minimum value between the internal thread connection strength of the coupling and the external thread connection strength.

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$$\boldsymbol{P_G = 0.95A_P U_P\left[1.008 - 0.0396\left(1.083 - \frac{Y_P}{U_P}\right)D\right]} \qquad (1)$$

In the formula, P_G is the casing body thread connection strength; Y_P is the minimum yield strength of the casing body material; U_P is the minimum tensile strength of the casing body material; A_P is the cross-sectional area of the plain-end pipe, where $A_P=0.7854(D^2-d^2)$; D is the outer diameter of the pipe; and d is the inner diameter of the pipe.

The internal thread connection strength of the casing coupling is:

$$\boldsymbol{P_j = 0.95A_c U_c} \qquad (2)$$

In the formula, P_j is the casing coupling thread connection strength; U_c is the minimum tensile strength of the casing coupling material; A_c is the cross-sectional area of the coupling, where $A_c = 0.7854\,(W_2 - d_1^2)$; d_1 is the diameter at the root of the coupling thread corresponding to the external thread end face under the make-up condition, calculated as $d_1=E_7-(L_7+I)T+0.062$. The value of I is 0.4 for a size of 114.3 mm, 0.5 for sizes from 127 to 339.7 mm, and 0.375 for sizes greater than 339.7 mm. The value of T is 0.0625 for sizes ≤ 339.7 mm and 0.0833 for sizes > 339.7 mm. L_7 is the length of perfect thread.

2.3. Triangular Thread

2.3.1. Triangular Thread Tooth Profile

The tooth profile is an equilateral triangle with a thread angle α = 60°. For the same nominal diameter, threads are categorized into coarse and fine threads based on pitch size. Fine threads have a similar tooth form to coarse threads but feature a smaller pitch, a smaller lead angle, better self-locking properties, and higher strength. However, fine threads are less wear-resistant and more prone to thread stripping. Coarse threads are generally used for common connections, while fine threads are often employed for small components.

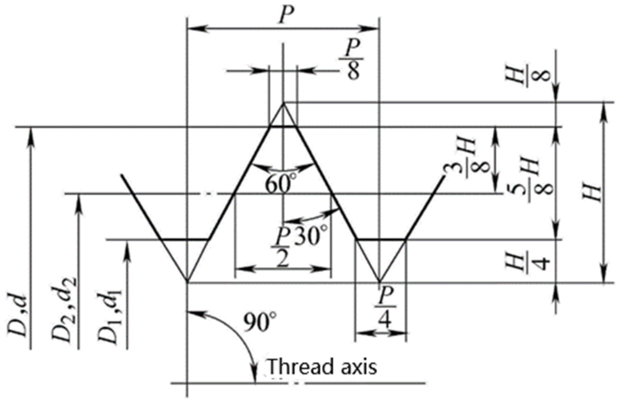

Fig 3. Standard Triangular Thread Tooth Profile

2.3.2. Basic Parameters of Triangular Threads

The major diameter of a thread refers to the diameter of an imaginary cylinder that coincides with the crest of an external thread or the root of an internal thread. Parameters include the nominal diameter, pitch diameter, lead, thread angle, and helix angle.

The working height refers to the effective pitch of the thread, which is the thread pitch minus half the thread height. For an isosceles triangular thread, the thread height is equal to one-third of the total thread depth, and the pitch is equal to twice the thread depth. Therefore, the working height is equal to two-thirds of the total thread depth.

2.3.3. Tensile Strength Design of Triangular Thread Joints

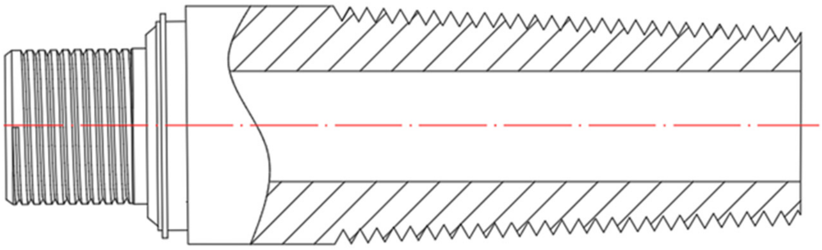

Fig 4. Standard Triangular Thread Model

The calculation of tensile strength for triangular thread joints requires consideration of the following factors:

(1) Material and strength grade of the thread joint;

(2) Linear contact area;

(3) Tightening force and thread spacing.

The specific calculation formula is as follows:

$$F = K \times A_s \times \sigma \quad (3)$$

In the formula, F represents the tensile strength of the thread joint, K is the correction coefficient, typically ranging from 0.6 to 0.7, with different adjustments required when considering axial and circumferential loads; A_s is the linear contact area of the thread joint, which can generally be calculated using thread calculation formulas; and σ is the material tensile strength of the thread joint.

2.3.4. Strength of Triangular Thread Connections

(1) Formula for calculating axial preload:

$$F_p = K * A_s * \sigma_P \quad (4)$$

In the formula,F_p represents the axial preload,K is the preload coefficient,A_s is the cross-sectional area of the thread, and σ_P is the yield strength of the material.

(2) Formula for calculating axial load strength:

$$F_t = 0.5 * A_s * \sigma_t \quad (5)$$

In the formula,F_t represents the axial load strength,A_s is the cross-sectional area of the thread, and σ_t is the tensile strength of the material.

(3) Formula for calculating bending load strength:

$$F_b = \frac{\pi * d^3 * \sigma_b}{12 * L} \quad (6)$$

In the formula, F_b represents the bending load strength,d is the thread diameter, σ_b is the bending strength of the material, and L is the thread length.

(4) Formula for calculating torsional load strength:

$$M_t = \frac{\pi * d^3 * \tau_t}{16 * L} \quad (7)$$

In the formula,M_t represents the torsional load strength,d is the thread diameter,τ_t is the shear strength of the material, and L is the thread length.

It should be noted that the parameters and material properties in the above formulas can be determined based on actual conditions. Meanwhile, to ensure the safety and reliability of the connection, a more comprehensive and integrated analysis is required. This includes considering loading conditions such as axial loads, bending loads, and torsional loads,

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calculating the overall strength of the connection, and determining whether the connection meets the strength requirements.

2.4. Thread Structure Design

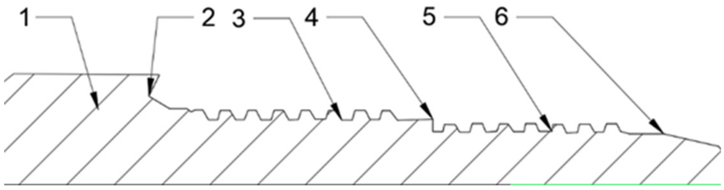

Fig 5. Gas-Sealing Threaded Connection Structure

This threaded connection structure employs a double-step internal and external thread design. The conical first sealing surface 2 and the second sealing surface are in an interference fit relationship, providing effective sealing between them. When the external thread joint 1 and the internal thread joint are connected, the high torque generated by the make-up machine ensures that the first sealing surface 2 and the second sealing surface 6 come into close contact, achieving metal-to-metal sealing. The stop shoulder surface 4 serves to prevent excessive torque during threading, which could otherwise damage the conical sealing surfaces.

3. Verification of Critical Components

Currently, three methods are available for analyzing tubing couplings: analytical methods, experimental methods, and finite element methods. The analytical method offers the advantage of clear and easy-to-understand concepts. However, if the model is inaccurate or not applicable to actual conditions, the analysis results may contain errors. The analytical method typically assumes that the connection components and materials are ideal and cannot account for real-world influences such as material defects or corrosion. In contrast, experimental methods can compensate for the limitations of analytical approaches, though they come with drawbacks such as high cost, lengthy duration, susceptibility of results to experimental conditions, and the inability to consider all scenarios. With the advancement of computer technology, finite element analysis has become more practical than both analytical and experimental methods.

Due to the complexity of tubing joint threads, constructing a three-dimensional finite element model would involve substantial computational effort. Therefore, most researchers adopt various simplified models, with axisymmetric models being the most common. The validity and rationality of such solutions have gained general acceptance in the engineering community.

3.1. Thread Strength Verification

According to API 5B specifications, a 139.7 × 9.17 mm P110BC casing was selected for strength verification. The tubing connection thread is external, while the well control controller connection thread is internal. For verification, only the central cross-section of the joint is considered, and the casing length is set to three times the length from the pipe end to the thread vanishing point. Additionally, the thread lead angle is neglected, the structure is assumed to be axisymmetric, and both the joint and tubing materials are assumed to be isotropic. The elastic modulus of the tubing and joint material is chosen as $E = 1.9 \times 10^5$ MPa, with a Poisson's ratio of 0.3. According to reference data, a 1000-meter-long tubing with an inner diameter of 76 mm weighs approximately 10,357.2 kg, resulting in a gravitational load of 200 kN on the tubing coupling.

During operation, the axial force borne by the tubing coupling is mainly concentrated at the triangular thread connecting to the tubing hanger or at the buttress thread connecting to the full-bore section. Since the triangular thread is the one adapted to the tubing hanger, its

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verification is not required here. Thus, the buttress thread of the tubing coupling needs to be verified.

Given the axial force F_f = 200 kN, the tubing coupling structure is shown in Fig 6.

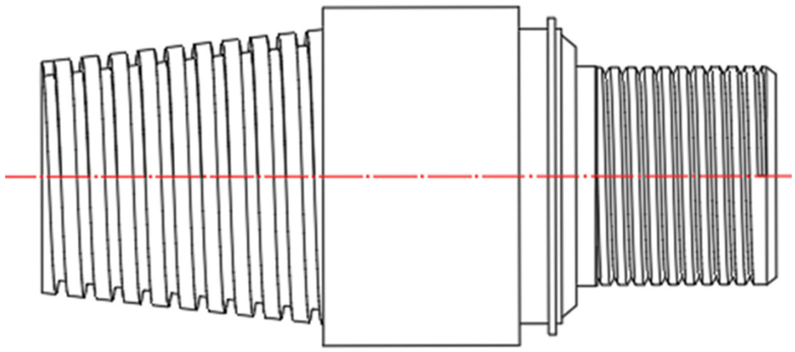

Fig 6. Tubing Coupling Structure

The material adopted for this verification is P110 steel, using a buttress-threaded pipe with dimensions of (φ139.7 × 9.17 mm). In tensile tests, this size of tubing exhibits a minimum yield strength of 758 MPa and a maximum yield strength of 965 MPa. Therefore, the yield limit of the tubing is taken as 758 MPa, and the ultimate strength is taken as 965 MPa. The tensile strength of the material is set to 965 MPa. Since the compressive strength of the material is significantly higher than its tensile strength, no further calculations are performed in this regard.

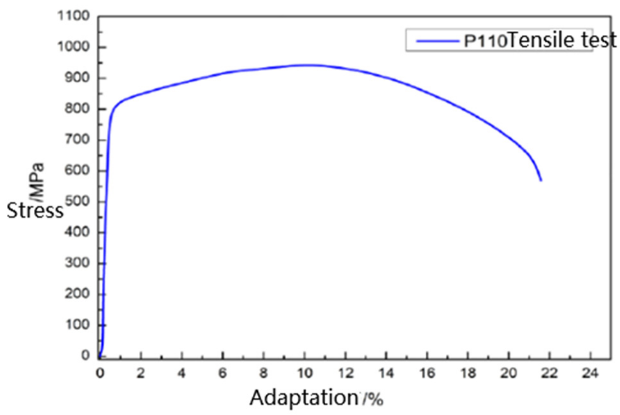

Fig 7. Stress-Strain Curve of P110 Steel from Tensile Test

(1) Strength Calculation of Thread Teeth

According to API specifications, the tensile strength of P110 steel is 965.3 MPa. The formula for calculating the thread cross-sectional area is:

$$\boldsymbol{A_s = \frac{\pi}{4} * \left[\left(D - \frac{0.64952}{P}\right)^2 - D^2\right]} \tag{8}$$

Where D is the thread outer diameter, in inches; P is the pitch, in inches.

Substituting the thread dimensions into the above formula yields:

$$D = 2.375A_s \tag{9}$$

D=π/4*[(2.375-0.64952/0.2)^2-2.375^2]

$=10.64mm^2$

The calculation formula for thread tooth strength is as follows:

$$P = \frac{0.7\sigma_y A_s}{0.144 + 0.006A_s} \tag{10}$$

Where P is the ultimate load of the thread tooth, in kN; σ_y is the tensile strength of the thread tooth material, in MPa; and A_s is the cross-sectional area of the thread, in mm^2.

Substituting σ_y and A_s into the thread tooth strength calculation formula yields:

P=0.7*965.3*10.64/(0.144 +0.006*10.64)=377.4kN

Therefore, the thread tooth strength of the API buttress thread made of P110 steel material is 377.4 kN. Based on the calculation results, it can be concluded that this thread meets the strength requirements.

(2) Tubing Coupling Strength Calculation:

According to API specifications, the formula for calculating the tensile strength factor F of the tubing is:

$$F = 0.72 - 0.0017d - 0.000007d^2 \tag{11}$$

Where d is the outer diameter of the tubing. With an inner diameter of 76 mm, the tensile strength factor F of the tubing is thus:

F=0.72-0.0017*2.992-0.000007*2.992 ≈0.561

The formula for calculating the tubing axial stress F_t is:

$$F_t = \frac{\left(Pd - \frac{Pd^2}{(4t^2)}\right)}{\left(\frac{d^2}{4} - \frac{(d-2t)^2}{4}\right)} \tag{12}$$

Where P is the internal pressure in MPa; d is the outer diameter of the tubing; and t is the wall thickness of the tubing.

Given an inner diameter of 76 mm and a wall thickness of 6.45 mm, we obtain d=2.992 in and t=0.254 in.

Therefore, the tubing axial stress

F_t=200 kN / (π * (76/2)^2) ≈ 0.141 MPa

The formula for calculating the tubing tensile strength is:

$$\sigma_t = \frac{(Pd - 2F_t)}{F} \tag{13}$$

Substituting the above calculation results into the formula yields:

σ_t = (Pd - 2 * 0.141)/0.561 ≈ 0.63

Therefore, the tensile strength of this P110 steel tubing is 0.63 MPa.

4. Conclusion

This paper conducted systematic design and analysis of the connection structure between the well control controller and the tubing hanger. The main conclusions are as follows:

(1) Through a comprehensive comparison of different methods such as threaded connection, flange connection, clamp connection, and welding, and considering the operational requirements of high pressure, high temperature, and frequent assembly/disassembly in oil and gas well downhole environments, the threaded connection was determined as the core connection scheme between the well control controller and the tubing hanger. This method offers comprehensive advantages in terms of structural compactness, load-bearing reliability, and field operability.

(2) A focused study was conducted on the mechanical properties and sealing mechanisms of API buttress threads and standard triangular threads. The design adopted a conical metal sealing surface structure featuring dual-step mating of internal and external threads. High-

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pressure gas sealing is achieved through the interference fit of the first and second sealing surfaces, and a stop shoulder is incorporated to prevent damage to the sealing surfaces caused by excessive assembly torque. This significantly enhances the sealing reliability and structural integrity of the joint under harsh operating conditions.

(3) Using a P110 grade, φ139.7×9.17 mm buttress thread joint as the research object, a strength verification model was established based on API specifications, supplemented by finite element analysis. The calculation results show that under an axial working load of 200 kN, the ultimate load-bearing capacity of the thread teeth is 377.4 kN, and the tubing coupling tensile strength meets the requirements, verifying the safety and feasibility of the selected material and structural design.

(4) This research employed a combined methodology of theoretical analysis, specification-based calculation, and finite element simulation. This approach ensured computational efficiency while improving the engineering credibility of the analysis results. Although reasonable simplifications were made regarding factors like the thread lead angle and material homogeneity in the study, the conclusions still hold good reference value for the design and selection of similar tubing hanger connection structures.

In summary, the dual-step sealing connection structure based on the API buttress thread proposed in this paper meets the strength and sealing requirements while also considering the convenience of on-site assembly. It provides a useful basis for the design and engineering application of key threaded connections in well control equipment. Subsequent work could further involve physical testing and fatigue performance research to comprehensively evaluate its long-term service reliability.

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