

Prediction of Sucker Rod-tubing Wear Depth in Surface Drive Screw Pump Production Wells

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Abstract

With the wide application of ground drive screw pump in the process of oil production, the wear problem of screw pump sucker rod-tubing is becoming more and more prominent. In order to systematically study the wear of the rod and tube of the screw pump production well and quantify the wear of the rod and tube, this paper establishes a calculation model of the contact force of the screw pump sucker rod by analyzing the force of the rod and tube string in the three-dimensional wellbore trajectory. Based on the indoor rod and tube wear simulation experiment, combined with the wear efficiency theory, a prediction model of sucker rod-tubing wear under different working conditions was established, and an example well calculation was carried out. The results show that the force of sucker rod is mainly affected by sucker rod size, submergence degree and other factors, and the wear of sucker rod and tubing is mainly affected by working time, rotational speed and wear efficiency. The research results can not only accurately carry out accurate quantitative calculation of downhole rod and tube wear, but also provide theoretical and technical basis for prediction of rod and tube wear depth.

Keywords

Rod Tube Wear; Wear Experiment; Contact Force; Wear Depth; Wear Coefficient; Prediction Model.

1. Introduction

Ground driven screw pump oil production technology is widely used in oil fields because of its simple structure, high pump efficiency and energy saving. With the passage of time, most of the domestic oil fields have entered the middle and late stage of exploitation. The phenomenon of rising water content and sand production is becoming more and more serious. The wear problem of sucker rod and tubing has become a common problem in oilfields. It not only increases the probability of sucker rod breaking off, shortens the pump inspection cycle, but also increases the number of workovers, which seriously restricts the improvement of production efficiency. In order to study the wear mechanism of the ground drive screw pump rod and predict the wear of the downhole rod, a lot of research work has been carried out. V. M. Ryazantsev et al. [1] calculated and compared the screw axial force of high pressure single screw pump, and modified the formula of screw axial force combined with production conditions. Ivanov et al. [2] proposed a method for calculating the fatigue strength of threaded screw of submersible centrifugal pump under the action of pulsating rupture force. A Yu Davydov et al. [3] found that the torsional vibration of the sucker rod string will occur during the operation of the ground drive screw pump. It is recommended to install a torsional vibration damper to maintain the stability of the sucker rod string, and the calculation of the damper parameters is given. Zhang et al. [4] analyzed the failure position and failure form of the sucker rod, and concluded that the number and installation position of the sucker rod centralizer lacked technical basis. Han et al. [5] measured the normal stress and eccentricity of the tubing

string caused by the fluid through experiments, and proposed comprehensive measures to avoid local wear of the sucker rod. Based on the three-dimensional trajectory of sucker rod string, Araújo et al. [6-8] proposed a new method for calculating the force of sucker rod string, deduced the mechanical analysis model of sucker rod string in three-dimensional directional well, and accurately analyzed the three-dimensional stress and dynamic state of downhole sucker rod string. Wu et al. [9-12] established the dynamic model of sucker rod, and studied the deformation of tubing sucker rod caused by the eccentricity of screw pump rotor. This method can effectively obtain the deformation and dynamic characteristics of rotating rod string. Sun et al. [13-16] proposed a new dynamic analysis method for the lateral vibration of sucker rod in tubing based on vibration theory. The lateral vibration model is suitable for the eccentric wear analysis of sucker rod tubing, which provides a new theoretical basis for the optimal configuration of centralizer. Although there are many researches on the wear of the screw pump rod and tube, the research on the quantitative calculation of the wear depth of the rod and tube is not systematic enough based on the force analysis of the rod and tube, and a set of calculation model for accurately predicting the wear depth of the rod and tube has not been formed. Therefore, a comprehensive solution to the complex problem of quantitative calculation of rod and tube wear in screw pump wells is still urgently needed.

Through theoretical deduction, physical experiment and field application, this paper systematically completed the quantitative calculation from force analysis to wear depth of screw pump rod and tube, and put forward effective measures to prevent and reduce rod and tube wear. The novelty of this study lies in the systematic quantitative calculation of the wear depth of the rod and tube based on the spatial force analysis of the screw pump rod and tube, which provides theoretical support and calculation methods for the prediction of rod and tube wear.

2. The Establishment of Sucker Rod Mechanical Model:

The sucker rod is the power transmission part of the ground drive device of the screw pump oil well. When the system is working, the sucker rod rotates at a high speed, transmits the ground torque to the downhole, and drives the screw pump rotor to rotate to extract the oil. The stress of downhole rod string is an important factor affecting the production of oil wells and the inspection cycle of screw pumps. Therefore, it is particularly important to study the force of sucker rod under working condition.

When the screw pump oil production system works normally, the downhole sucker rod string rotates at a constant speed. At this time, the oil well production is stable, and the system load tends to be stable. In this process, the axial force of the sucker rod string can be obtained from the following formula:

$$F = F_w + F_b - F_l - F_f \tag{1}$$

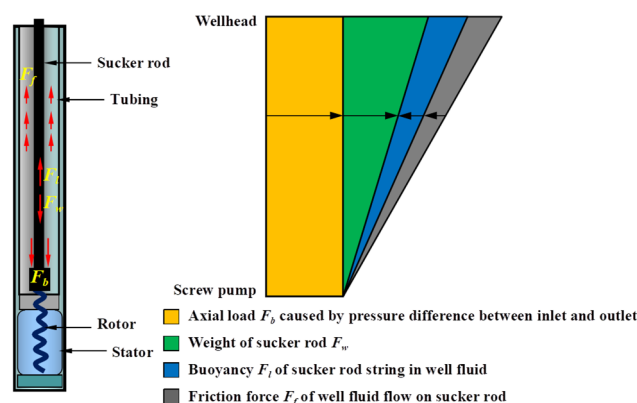


Fig 1. Axial force of sucker rod and its composition diagram

Where: F is the total axial force on the sucker rod, N; F_w indicates the weight of the sucker rod, N; F_b is the axial force caused by the pressure difference between the inlet and outlet of the pump, N; F_l is the buoyant force of the sucker rod in the oil, N; F_f is the friction force generated by the upward flow of well fluid on the sucker rod, N; (In Fig 1)

Eqs. (2)-(5) are the detailed expressions of each axial component:

$$F_w = mg = \sum_{i=1}^N \rho_{bi} g A_i L_i \tag{2}$$

$$F_l = \sum_{i=1}^N \rho_{li} g A_i L_i \tag{3}$$

$$F_b = \left[8eD + \frac{\pi}{4} (D^2 - D_r^2) \right] \Delta P \tag{4}$$

$$F_f = 2 \sum_{i=1}^N \pi \mu_i v_i L_i \frac{m^2 - 1}{(m^2 + 1) \ln m - (m^2 - 1)} \tag{5}$$

Where, ρ_{bi} is the density of the sucker rod string in section i , kg/m^3 ; g is the acceleration of gravity, m/s^2 ; A_i is the cross-sectional area of the sucker rod string in section i , m^2 ; L_i is the length of the sucker rod in section i , m ; ρ_{li} is the fluid density of the sucker rod string in section i , kg/m^3 ; μ_i is the average viscosity of the well fluid, $\text{Pa}\cdot\text{s}$; v_i is the average flow rate of well fluid m/s ; D is the rotor cross-section diameter, m ; D_r is the sucker rod diameter, m ; D_t is the inner diameter of the tubing, m ; m is the ratio of the inside diameter of the tubing to the diameter of the sucker rod.

In this process, the axial torque of the sucker rod string can be obtained from Equation (2-6):

$$T = T_f + T_b + T_r + T_s \tag{6}$$

Where: T is the total torque of the sucker rod, $\text{N}\cdot\text{m}$. T_f is the torque generated by the stator and rotor initial interference, $\text{N}\cdot\text{m}$; T_b is the torque caused by the pressure difference between the inlet and outlet of the pump, $\text{N}\cdot\text{m}$; T_r is the friction torque between the sucker rod and the well fluid, $\text{N}\cdot\text{m}$; T_s is the friction torque between sucker rod, tube and centralizer, $\text{N}\cdot\text{m}$; (In Fig. 2)

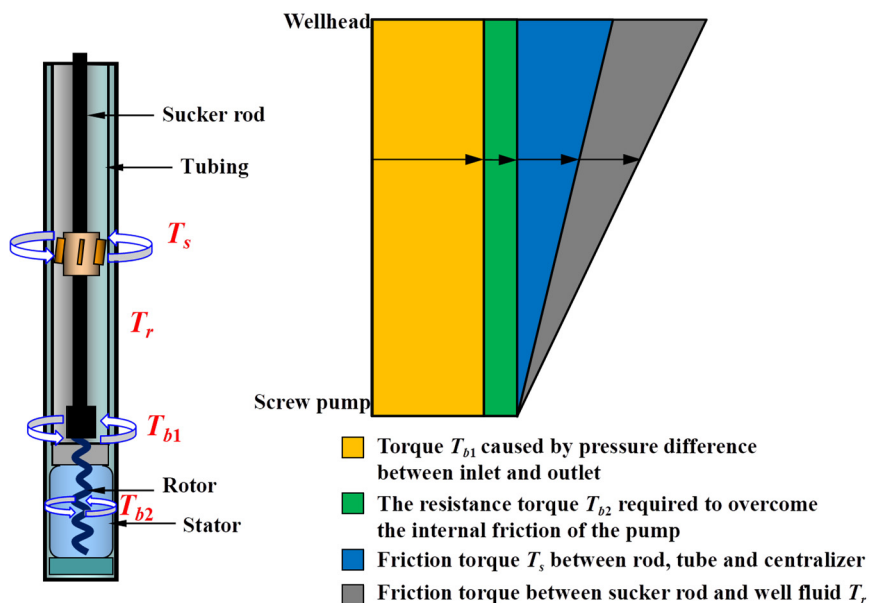


Fig 2. Sucker rod torque and its composition diagram

Eqs. (7)-(10) are the detailed expressions of each torque:

$$T_f = 91.3\delta_0 - n^{0.45} + 46.5 \tag{7}$$

$$T_b = \frac{2eDT_d}{\pi} \Delta P \tag{8}$$

$$T_r = 10^{-2} \sum_{i=1}^N \frac{\pi \mu_{li} \omega D_r^2 D_t^2}{D_t^2 - D_r^2} \tag{9}$$

$$T_s = \frac{1}{2} \sum_{i=1}^N D_r f (\rho_{bi} - \rho_{li}) g A_i L_i \tag{10}$$

Where n is the rotor speed and r/min. δ_0 is the initial interference value between the stator and the rotor, m; T_d is the stator lead, m; ΔP is the inlet and outlet pressure difference of the pump, MPa; μ_{li} is the viscosity of well fluid corresponding to the sucker rod in Section i , Pa·s; ω is the angular velocity of the sucker rod, rad/s; D_t is the inner diameter of the tubing, m; D_r is the sucker rod diameter, m; f is the friction coefficient; ρ_{bi} is the density of sucker rod string in section i , kg/m³; ρ_{li} is the fluid density of the sucker rod string in section i , kg/m³; A_i is the cross-sectional area at the sucker rod in section i ; g is the acceleration of gravity, m/s²; L_i is the length of the sucker rod in section i , m;

3. Prediction Model of Sucker Rod-tubing Wear in Screw Pump Production Wells

3.1. Sucker Rod-tubing Wear Prediction Model

Based on the analysis of the change law of the contact load between the sucker rod and the tubing during the lifting process of the screw pump and the relative slip analysis, the prediction method of the wear amount of the rod and tubing is established by using the energy transfer principle and the wear experiment data.

In the casing wear prediction theory, the well-developed and widely used method [17] is the linear 'wear-efficiency' model proposed by White and Dawson. They believe that in the process of friction and wear, part of the friction work is converted into friction heat, and the other part is manifested as casing wear. The calculation formula of casing wear volume is:

$$V_w = \int_0^t k \mu F_n \pi d_r \omega dt \tag{11}$$

Where, V_w is the wear volume, m³; k is the wear efficiency, Pa⁻¹; μ is the friction coefficient; F_n is the contact force between the sucker rod and the tubing, N; d_r is the sucker rod diameter, m; ω is the sucker rod speed, r/min; t is wear time, s.

A geometric model for calculating the maximum wear depth was established for the crescent-shaped wear marks formed on the inner wall of the tubing after wear. The cross section of sucker rod and tubing is taken as the research object, and the coordinate system of Fig 3 is established.

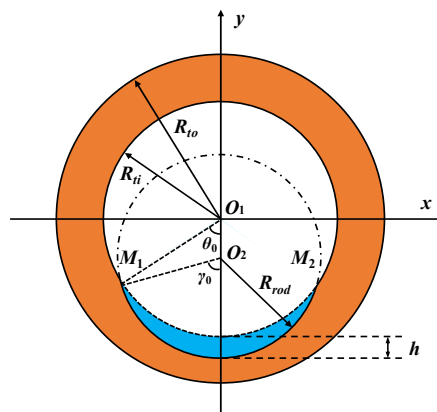


Fig 3. Sucker rod-tubing wear diagram

In Fig 3, the maximum circle is the outer wall circle of the tubing, the middle circle is the inner wall circle of the tubing, and the minimum circle is the outer circle of the sucker rod. The two points intersecting the cross section of the sucker rod and the tubing are the boundary points of the wear area, and the part intersecting the sucker rod and the tubing is the wear area of the tubing on the cross section. Integral by the analytical method, the area of wear area is:

$$\begin{aligned}
 A &= \int_{x_1}^{x_2} (\sqrt{R_r^2 - x^2} + (R_{ti} - R_r + h) - \sqrt{R_{ti}^2 - x^2}) dx \\
 &= (R_{ti} - R_r + h)x_2 + R_r^2 \arcsin \frac{x_2}{R_r} - R_{ti}^2 \arcsin \frac{x_2}{R_{ti}}
 \end{aligned}
 \tag{12}$$

Where R_r is the sucker rod radius, m; R_{ti} is the inner wall radius of the tubing, m; h is the maximum wear depth of tubing; x_1 and x_2 are the horizontal coordinates of the wear boundary, whose expression is:

$$x_2 = -x_1 = \sqrt{R_{ci}^2 - \left[\frac{R_y^2 - R_{ci}^2 - (R_{ci} - R_y + h)^2}{2(R_{ci} - R_y + h)} \right]^2}
 \tag{13}$$

According to the formula (3-1) ~ (3-3), the wear depth under specific working conditions can be obtained by iterative algorithm. The specific process is as follows :

Firstly, on the basis of known calculation basic parameters (well depth, pump hanging depth, liquid level depth, sucker rod size, tubing size, pump parameters, friction coefficient, wear efficiency, etc.), the sucker rod and tubing are divided into micro-segments. Then, the micro-element section of the sucker rod is selected to calculate and obtain the distribution of the sucker rod force along the well depth, and the wear volume distribution of the sucker rod and the tubing is calculated according to the wear prediction model. Finally, according to the analysis of wear geometry, the wear volume depth distribution of sucker rod and tubing is calculated.

3.2. Sucker Rod-tubing Wear Experiment

Wear coefficient is a parameter describing the surface wear degree of friction materials, which represents the material mass loss per unit area in unit time. Wear coefficient is a key parameter in the process of sucker rod-tubing wear prediction in screw pump wells, which has a very important influence on wear prediction. In this study, the wear mechanism of sucker rod-tubing under different working conditions was analyzed through the wear experiment of sucker rod-tubing, and the wear coefficient of sucker rod and tubing was obtained. The designed experimental device consists of a drive motor, a bottom plate, a load arm, a mud tank, a speed control unit and a test piece. Before the experiment, the weight of the tubing sample was measured as the initial weight. In this experiment, the normal load is applied between the sucker rod specimen and the tubing specimen through the self-weight and the load arm. When the sucker rod sample is driven to rotate at a certain speed, friction and wear will occur between the friction surface of the sucker rod and the tubing. After the tubing sample is worn at a specific test time, its residual weight and wear morphology are measured. In order to investigate the influence of different sand content and different water content on the wear of sucker rod-tubing in detail, the experimental results under different working conditions were analyzed and compared (In Fig 4 and 5).

It can be seen from Fig 4 that the sand content has little effect on the wear performance. With the increase of sand content, the wear amount increases gradually. From the 3.3 diagram, it can be seen that with the increase of water content, the friction and wear of the eccentric wear of the matching pair becomes more and more serious. Taking the sucker rod as an example, the minimum loss is 0.733 mg, the maximum loss is 5.27 mg, and the increase is extremely obvious.

According to the Fig of 4 and 5, it can be seen that the wear amount of tubing is higher than that of sucker rod under the same working conditions.

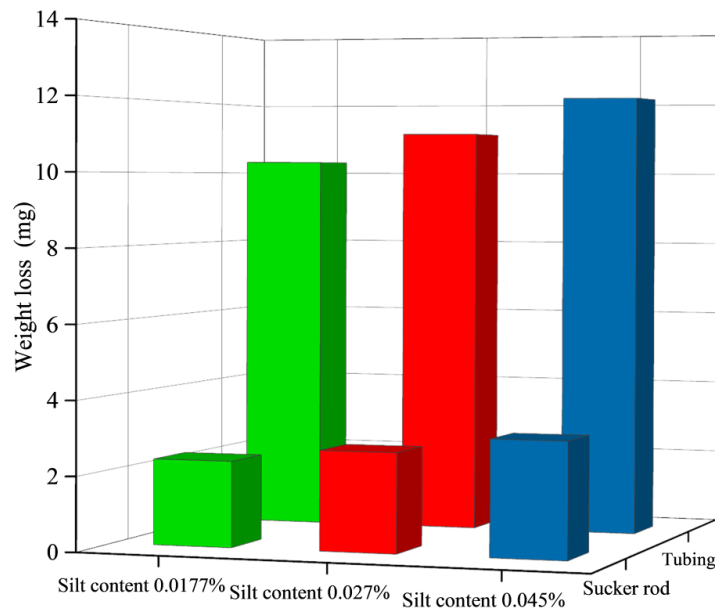


Fig 4. Wear loss of sucker rod-tubing with different sand content

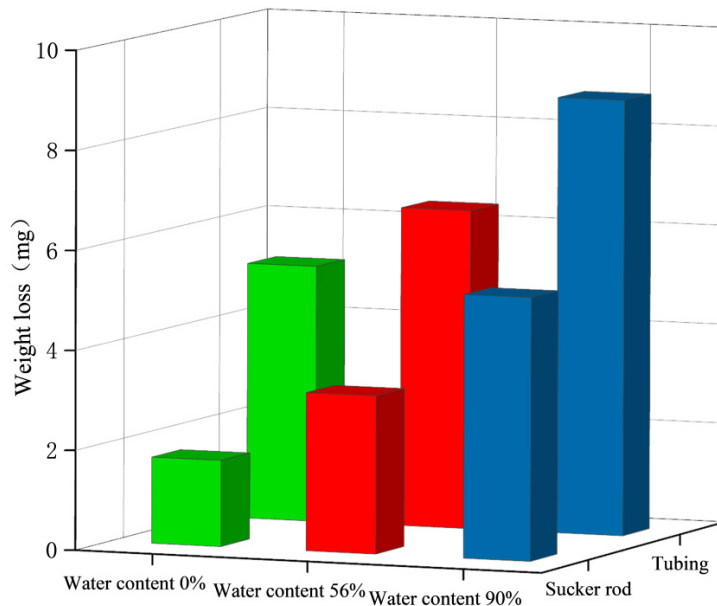


Fig 5. Wear amount of sucker rod-tubing with different water content

According to the wear efficiency model, the wear coefficient is a function of weight loss, rotational speed and contact force, expressed as :

$$k = \frac{\Delta V}{W_t} = \frac{\Delta m / \rho}{\mu F \cdot \pi D_r \cdot \omega t} \tag{14}$$

Where, ΔV is the wear volume of the sucker rod or tubing, m^3 ; W_t is the work done by friction, J; Δm is the wear loss of the sucker rod or tubing, kg; ρ is the density of the sucker rod or tubing, kg/m^3 ; F is the contact load between the sucker rod and the tubing, N.

Therefore, the wear coefficient of sucker rod-tubing under different working conditions is calculated by data processing, as shown in table 1. It can be seen from the table that the wear

efficiency of sucker rod is 0.7~5.06 ($\times 10^{-14}Pa^{-1}$), and the wear efficiency of tubing is 4.95~11.62 ($\times 10^{-14}Pa^{-1}$).

Table 1. Sucker rod-tubing wear coefficient under different working conditions

number	medium	Rod tube combination	Sucker rod wear quantity (mg)	Tubing wear quantity (mg)	Sucker rod wear efficiency ($10^{-14}Pa^{-1}$)	Tubing wear efficiency ($10^{-14}Pa^{-1}$)
1	Moisture content 0% Sand content is 0.0177%	N80*H	0.733	5.16	0.70	4.95
2	Moisture content 56% Sand content is 0.0177%	N80*H	1.27	6.42	1.22	6.16
3	Moisture content 90% Sand content is 0.0177%	N80*H	5.27	9.77	5.06	9.38
4	Moisture content 56% Sand content is 0.0177%	J55*H	2.31	10.3	2.21	9.89
5	Moisture content 56% Sand content 0.027%	J55*H	2.67	11.1	2.56	10.66
6	Moisture content 56% Sand content is 0.045%.	J55*H	3.10	12.1	2.98	11.62

4. Example Well Analysis

4.1. XX Well Rod String Mechanics and Wear Calculation

According to the established force prediction model and XX screw pump production well parameters, the distribution of sucker rod contact force along the well depth can be calculated, as shown in Fig 6. The maximum contact force between the sucker rod and the tubing is 150.77 N, which appears at a well depth of 500 m.

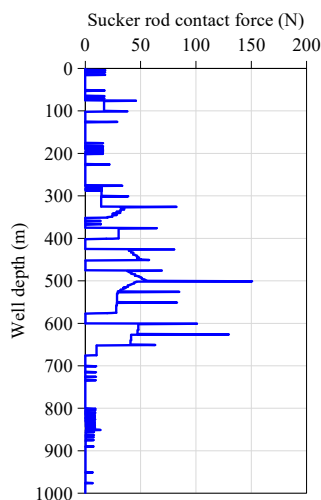


Fig 6. Calculation results of sucker rod contact force in XX well

Based on the above calculation results of sucker rod force, the wear of sucker rod and tubing in XX well is calculated and analyzed by using the established calculation model of rod and tubing wear in screw pump production well. The working time is 243 days, and the results are shown in Fig 7.

It can be seen from Fig 7 that after 243 days of operation, the maximum wear depth of the sucker rod is 1.55 mm, and the maximum wear depth of the tubing is 2.20 mm, both of which appear at a well depth of 500 m. The experiment proves that the wear efficiency of the tubing is higher than that of the sucker rod, so the wear rate of the tubing is also higher than that of the sucker rod in the same friction pair.

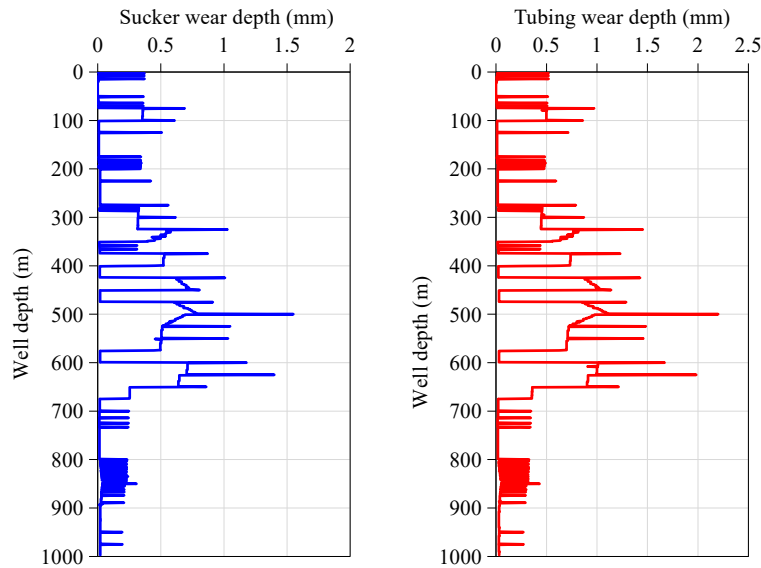


Fig 7. Calculation results of rod and tube wear in XX well

4.2. Prevent and Reduce Sucker Rod-tubing Wear

4.2.1. Analysis of the Influence of Different Factors on the Stress of the Rod Tube

According to the wear efficiency model, the prevention and reduction of friction between rod and tube can be achieved by reducing the contact force. However, the main factors affecting the force of the sucker rod are the size of the sucker rod and the sinking degree of the pump. The influence of sucker rod size and pump submergence on the force of sucker rod is studied by using the established force calculation model of rod string in screw pump production well. The results are shown in Fig 8 and Fig 9. It can be seen from Fig. 8 that as the size of the sucker rod increases, the contact force of the sucker rod gradually increases. When the sucker rod size increases from 19 mm to 22 mm and 25 mm, the maximum contact force of the sucker rod increases from 120.59 N to 134.65 N and 150.77 N ; It can be seen from Fig 9 that the submergence degree of the pump affects the force of the sucker rod by affecting the pressure difference between the inlet and outlet of the pump. With the increase of pump submergence, the pressure difference between the inlet and outlet of the pump increases, and the contact force of the sucker rod increases gradually. When the pump submergence increases from 400 m to 600 m and 800 m, the maximum contact force of the sucker rod increases from 124.34 N to 150.77 N and 177.20 N.

With the increase of the size of the sucker rod, the contact force of the sucker rod increases gradually. The simulation results show that compared with the 25mmD sucker rod, the wear rates of 25 mmD+22mmD, 25mmH and 25mmH+22mmH sucker rods are reduced by 7%, 9% and 15% respectively. In addition, with the increase of pump submergence, the pressure difference between the inlet and outlet of the pump increases, and the contact force of the

sucker rod gradually increases. The optimal submergence of the screw pump well is recommended to be 200-300 m.

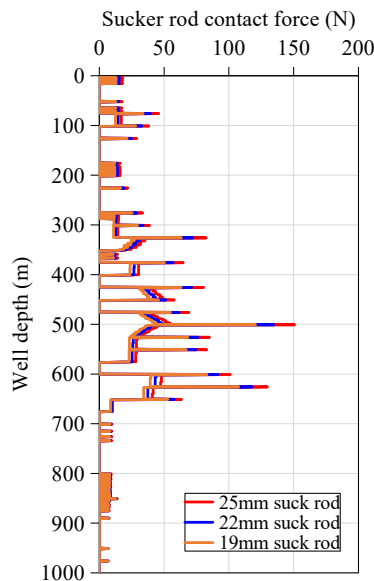


Fig 8. The influence of sucker rod size on contact force distribution

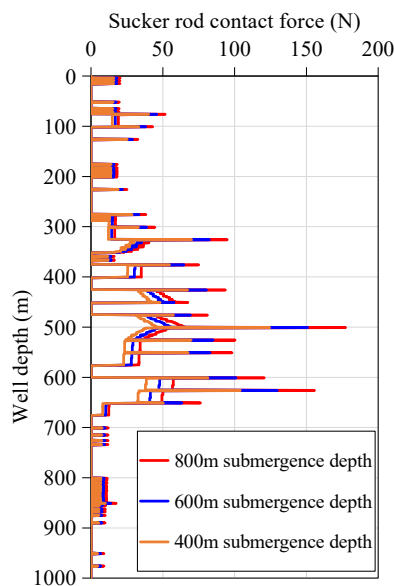


Fig 9. The influence of pump submergence on contact force distribution

4.2.2. Analysis of the Influence of Different Factors on the Wear of Rod and Tube

In addition, according to the wear efficiency model, the main factors affecting the wear of the rod and tube are working time, rotational speed and wear efficiency. The influence of different factors on the wear amount was studied by using the established rod and tube wear calculation model. The results are shown in Fig 10-Fig 12.

In order to slow down the wear rate of the rod tube, the following measures can be taken:

- (1) For high-speed wells, it is recommended to appropriately reduce the rotation speed of the screw pump sucker rod to minimize the wear of the rod and pipe.
- (2) The wear efficiency of sucker rod and tubing can be greatly reduced by taking appropriate measures of sand cleaning and wax prevention, so as to slow down the wear of rod and tubing.

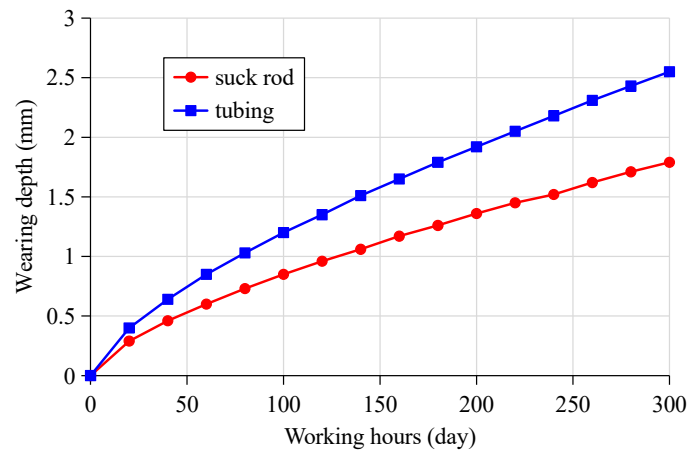


Fig 10. Influence of working time on wear loss

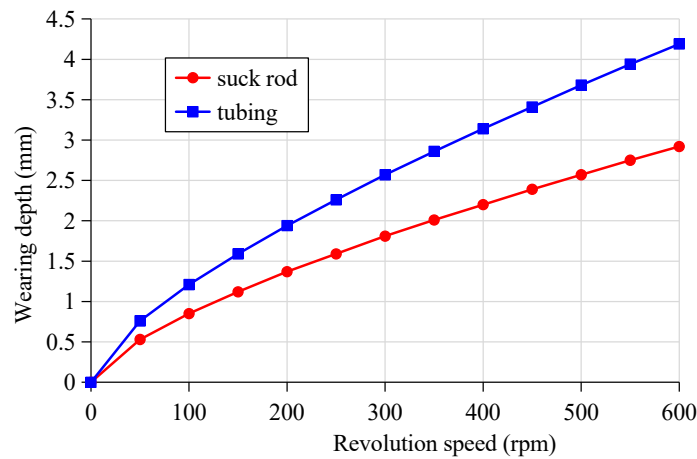


Fig 11. The influence of rotational speed on wear loss

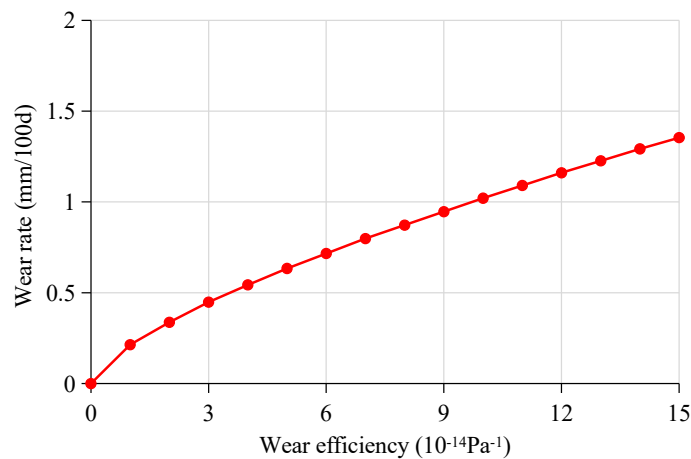


Fig 12. Effect of wear efficiency on wear

5. Conclusion

- (1) The stress and wear of the rod string are calculated for the typical screw pump oil well (XX well). The serious wear of sucker rod and tubing generally occurs in the lower part of the wellbore, especially within 200 m above the pump, which is basically consistent with the change trend of contact force, mainly affected by the inclination and bending of the wellbore.
- (2) The main factors affecting the force of the sucker rod are the size of the sucker rod and the sinking degree of the pump. With the increase of sucker rod size, the axial force, contact force

and torque of sucker rod increase gradually. The pump submergence affects the force of the sucker rod by affecting the pressure difference between the inlet and outlet of the pump. With the increase of pump submergence, the pressure difference between the inlet and outlet of the pump increases, and the contact force of the sucker rod increases gradually. The best submergence degree of screw pump well is recommended to be 200 ~ 300 m.

(3) The main factors affecting the wear of rod and tube are working time, rotational speed and wear efficiency. The wear depth increases nonlinearly with the increase of working time, rotating speed and wear efficiency. As the wear progresses, the increase rate of wear depth gradually slows down. In order to slow down the wear rate of the rod and tube and prolong the pump inspection cycle, the following measures can be taken: ① For high-speed wells, it is recommended to appropriately reduce the rotation speed. ② The wear efficiency of sucker rod and tubing can be greatly reduced by taking appropriate measures of sand cleaning and wax prevention, so as to slow down the wear of rod and tubing.

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