Exploration and practice of integrated control technology for tubing and sucker rod lopsided wearing in directional well

To cite this article: Jing Guo et al 2018 IOP Conf. Ser.: Earth Environ. Sci. 208 012021

View the article online for updates and enhancements.
Exploration and practice of integrated control technology for tubing and sucker rod lopsided wearing in directional well

Jing Guo 1, 2, *, Song Fan 1, 2, Tao Liu 3, Mei Lu 1, 2, Yang Yao 1, 2, Yi Liang 1, 2, Chun Zhao 1, 2, Haixia Shi 1, 2

1. Oil & Gas Technology Research Institute Changqing Oilfield Company, Xi’an, China.
2. National Engineering Laboratory for Exploration and Development of Low-Permeability Oil & Gas Fields, China.
3. Changqing Oilfield Branch Company Oil Production Plant NO.6, China.

*Corresponding Author: tuhaihai@126.com

Abstract. Changqing oil field generally used sucker rod pump. In 2015, the maintenance operations reached 42 thousand times, the cost is about 550 million RMB, the work caused by tubing and sucker rod lopsided wearing accounts for 42.8% of the total. This paper focused on the main factor of lopsided wearing which caused high frequency of maintenance work, a three-dimensional mechanical simulation model of sucker rod string was established based on the analysis of borehole trajectory, rod mechanics; A model for calculation the neutral point of double material composite pipe and steel tubing is carried out; The calculation method of allowable stress is modified; at the same time, the application conditions of the mature process is standardized, to achieve the integration of technology management. The sucker rod lateral force dynamic distribution and allowable stress calculation method, the sucker rod parameter optimization and real-time warning, optimization of structure and the amount of wear resistant pipe string have been applied in oilfield. Compared with 2015, The number of maintenance operations decreased more than 6000 wells, operation frequency by 0.99 times / year - wells decreased to 0.85 times / year - wells, which is composed of 14 thousand and 500 well tube and rod failure wells decreased to 13 thousand and 300 wells, decreased 8%, annual cost savings of nearly 60 million RMB. It will have important guiding significance to prolong the pump checking period and cost control.

Key words: Cost cutting and improve performance; High-frequency well control; Tube failure well; Changqing oil field.

1. Introduction
Tubing and sucker rod wearing happens to directional wells in domestic and overseas oil fields. According to foreign reports on McElroy oil field, rod pumping wells often experience tubing and sucker rod wearing and corrosion under the conditions of high water content, long stroke, heavy load and low production in oil wells. In China, tubing and sucker rod lopsided wearing exists in Dagang, Jilin and...
The tubing and sucker rod lopsided wearing in direction well must be mainly attributed to such factors as wellbore trajectory, forces on sucker rod string, production parameters, and downhole environment.

2.1. Complex Borehole Trajectory
Changqing oil field is developed in the form of cluster well group. In recent years, the increasing production of oil field has led to the gradual increase of well depth, and the larger proportion of large well group (with 8-15 wells or more). Due to the requirements for protection against collision, shunning barriers and large displacement scoring, more intervals appear with large well deflection and high overall angle change rate, while the wellbore trajectory is complex. During the production of sucker rod pumping well, the axial force of sucker rod generates a horizontal component, which causes the contact friction between tubing and sucker rod, and then their wearing.

2.2. Forces on Rod String
During the reciprocating movement of sucker rod, sucker rod and tubing are constantly exposed to alternating loads. Under upward stroke, sucker rod pump drives the movement of sucker rod upwards, so the sucker rod is entirely under the effect of pull force. Under downward stroke, sucker rod is pulled at its top and pushed at its bottom due to the joint effect of forces. There is a point between the pull and push forces on the sucker rod, which is immune to both forces, so it is subject to zero force. This point is called neutral point. The portion of sucker rod under this neutral point loses its stability and is then bent under pressure, causing the friction of the spirally bent lower portion of sucker rod string against tubing, and then the lopsided wearing. Consequently, this leads to the tubing and sucker rod wearing, resulting in broken rod or leaking tubing.

2.3. Production Parameters
Meanwhile, rod string lopsided wearing relates to production parameters. Larger pump setting depth and higher frequency of stroke result in stronger lateral force and severer lopsided wearing. During the reciprocation of sucker rod, the lateral force varies significantly. The increasing frequency of stroke leads to higher frequency of sucker rod reciprocation, which causes more frictions and collisions between sucker rod and tubing, and then severe lopsided wearing.

2.4. Complicated Wellbore Environment

| Factor                          | Influence                                                                 |
|---------------------------------|---------------------------------------------------------------------------|
| High water content              | Deteriorate the lubrication on the surface of tubing and sucker rod to increase the downward resistance, which causes the bending of rod string and speeds up lopsided wearing |
| High mineralization of produced fluid | Cause the electro-chemical corrosion to tubing and sucker rod, which speeds up the corrosion fatigue of sucker rod          |
| Sand content of produced fluid  | Increase the wear rate and coefficient of sucker rod and tubing, which worsens the tubing and sucker rod wearing          |
| Wax deposition and scaling      | Cause the bending of sucker rod string above a point of wax deposition and scaling due to its exposure to higher friction against fluids, which results in lopsided wearing. |
Tubing and sucker rod lopsided wearing is worsened under the complicated wellbore environment, e.g. physical properties of crude oil with high water content and high mineralization in oil well, sand content, wax deposition and corrosive media in drilling fluid.

3. Technical Protection against Lopsided Wearing

3.1. Improved Model for Forces on Rod String Based on Three-dimensional Borehole Trajectory

It is always difficult to carry out the 3D mechanical calculations of rod string in China, and only RODSTAR from the United States has a feature of partial 3D analysis. Utilizing borehole trajectory, this paper introduces the approach of dividing wellbore into several sections and then calculating the forces on each section. Through mathematical description, borehole trajectory is directly used in calculations, while 3D mechanical calculations are conducted to find out the forces applied onto rod string, and viscosity resistance is modified in the meantime. In this way, it is possible to accurately analyze the strength and direction of axial and lateral forces in space and time during the movement of rod string, find out the law of their variation, and then develop suitable protective measures against lopsided wearing at any point of sucker rod and tubing.

The two-order 3D nonlinear partial differential equations are as follows:

\[
\begin{align*}
\rho \cdot A_r \frac{\partial u_{1,1}}{\partial t} &= \frac{\partial f_s}{\partial s} + \rho \cdot A_r \cdot g \cdot \cos \alpha + F_{cf} + F_{ct} + F_{fr} \\
\frac{1}{A_r \cdot E_s} \frac{\partial f_s}{\partial t} &= \frac{\partial u_{1,1}}{\partial s} - K_u \cdot s \\
\rho \cdot A_r \frac{\partial u_{2,1}}{\partial t} &= K_f \cdot \frac{\partial^2 M_{2,1}}{\partial s^2} - \tau \frac{\partial M_{1,1}}{\partial s} - \frac{\rho \cdot A_r \cdot g}{K} \frac{d \alpha}{ds} \sin \alpha + q_{2,1} \\
\frac{1}{E_s \cdot I_s} \frac{\partial M_{2,1}}{\partial t} &= -\tau \frac{\partial^2 u_{2,1}}{\partial s^2} - \frac{1}{A_r} \frac{\partial M_{1,1}}{\partial s} \\
\rho \cdot A_r \frac{\partial u_{1,2}}{\partial t} &= \frac{\partial^2 M_{1,2}}{\partial s^2} - \tau \frac{\partial M_{2,2}}{\partial s} - \frac{\rho \cdot A_r \cdot g}{K} \frac{d \phi}{ds} \sin \alpha + q_{1,2} \\
\frac{1}{E_s \cdot I_s} \frac{\partial M_{1,2}}{\partial t} &= -\tau \frac{\partial^2 u_{1,2}}{\partial s^2} - \frac{1}{A_r} \frac{\partial M_{2,2}}{\partial s}
\end{align*}
\]

Where: \( \alpha \): well deflection, \( \circ \); \( A_r \): cross section of sucker rod string, cm\(^2\); \( E_s \): elastic modulus of rod string, Pa; \( F_{cf}, F_{ct}, F_{fr} \): viscous friction of fluid against sucker rod, tubing and coupling, N; \( M1 \): torque, Nm; \( M2, M3 \): bending moment, Nm; \( s \): borehole arc length, cm;
Comparison shows the consistency between 3D force analysis results and measured values. Rod string optimization measures mainly include optimizing the design of rod string combination, determining the setting position and distribution of centralizers, and choosing the reasonable setting depth of sucker rod pump. The findings are as follows:

(1) Due to the fluctuation of lateral force, the maximum lateral force within the stroke cycle shall be taken in the design of centralizer. During the design, attention should be paid to both the strength and direction of lateral force. Centralizers must be arranged more densely in any well section subject to varying lateral force. Two-directional protective coupling is designed for the position subject to two-directional lopsided wearing.

(2) By lifting and lowering the depth of pump, tubing and sucker rod lopsided wearing is alleviated. The setting position of sucker rod pump should avoid the wellbore kickoff point. The end of sucker rod near the pump should be set into straight well section and stably deflected section.

(3) Reasonable stroke and frequency should be maintained. On one hand, lateral and axial loads subject to long stroke and low frequency are better than the combination of short stroke and higher frequency. On the other hand, more frictions and collisions happen to tubing and sucker rod under high frequency, which worsens wearing. Meanwhile, sucker rod pump of small diameter should be selected as much as possible, since small diameter can undermine the effect of lateral force.
3.2. Modified Method for Calculating the “Neutral Point” in Combinational Pipe String of Composite Pipe + Steel Tubing

For their favorable protection against corrosion and wearing, composite pipes including high-molecular weight and polyethylene lined pipe are often used in the wells with complicated wellbore environment and severe lopsided wearing. However, they are often combined with common tubing to form combinational pipe string at the site for protection in key well sections, so as to reduce costs. Due to large differences in size, structure, physical and chemical properties between these pipes and tubing, this pipe string is often exposed to different forces from ordinary tubing. Hence, the design of this combinational pipe string should be different from that of ordinary steel tubing, and should be modified.

Calculation of “neutral point”:

\[ L = 4\left(\frac{\pi}{4} \cdot d^2 f_{\text{cil}} + P_{\text{Downward}} + P\right) / \pi d^2 \rho g \]  

Where:
- \( x_L \) — distance from pump, i.e. position of neutral point, m;
- \( P \) — axial load causing the bending of sucker rod, N;
- \( d \) — diameter of sucker rod string, m;
- Foil — fluid pressure acting on plunger, Pa;
- \( \rho \) — density of sucker rod material, kg/m³;
- \( g \) — gravitational acceleration, 9.81 m²/s.

The actual range of rod string with lopsided wearing is greater than the calculated range of neutral point. There is still severe lopsided wearing at 50-100m in the upper portion of wear-resistant pipe.

After comprehensively considering such factors as wellhead back pressure \( p \), viscosity \( \mu \), centralizer friction \( F \), inside diameter variation of wear-resistant pipe \( \Delta d \), and elastic modulus of pipe material \( E \), the method for calculating the neutral point in the combinational pipe string of composite pipe and steel tubing is modified as follows:

\[ L' = f\left(L, p, \mu, F, \Delta d, E\right) \]  

This modified method for “neutral point” provides the design approach and theoretical basis for the application of wear-resistant pipe. After modification, the range of neutral point is approximate to the actual range of pipe string with lopsided wearing. Modification helps eliminate the contradiction of “poorer protection against wearing if too few, lower cost effectiveness if too many” in the application of composite wear-resistant pipe.

![Fig. 4 Schematic diagram of neutral point variation after modification](image-url)
3.3. Modified Method for Calculating Allowable Stress of Grade H Ultrahigh Strength Sucker Rod

The design of sucker rod string often relies on API modified Goodman stress diagram, which requires actual pressure on sucker rod no higher than maximum allowable stress during service. Meanwhile, maximum allowable stress is determined by the material, strength, load, and operating environment of sucker rod, so its accuracy directly affects the reasonableness of sucker rod design.

\[
\sigma_{\text{all}} = \left( \frac{T}{2K} + \left( 1 - \frac{\alpha}{2K} \right) \sigma_{\text{min}} \right) \cdot SF
\]  

In the above equation, when the ratio of tensile strength and yield strength is \( \alpha = 1.75 \) and pulse safety coefficient is \( K = 2 \), the modified Goodman stress method is obtained as shown in Equation (6). Hence, the key to the calculation of API maximum allowable stress for Grade H is to obtain the ratio of tensile strength and yield strength through indoor test.

\[
\sigma_{\text{all}} = (0.25T + 0.5625 \sigma_{\text{min}}) \cdot SF
\]  

Universal tester is employed in the tension test of Grade H sucker rod. The stress generating 0.2% residual deformation is taken as its yield strength. Hence, the ratio of tensile strength and yield strength is \( \alpha = 1.07 \text{--} 1.20 \), which is substituted into Equation (5). Taking \( K = 2 \), a new approach is developed to obtain the allowable stress of Grade H ultrahigh strength sucker rod.

\[
\sigma_{\text{all}} = (0.25T_H + 0.7163 \sigma_{\text{min}}) \cdot SF
\]  

Fig. 5 Modified Goodman stress diagram

This new approach is applied to calculate the allowable stress of Grade H rod, which widens the range of stress Grade H rod is able to withstand. By combining it with the calculation of forces on 3D borehole rod string and the prediction of the load at suspension point, the method for optimizing the design of ultrahigh strength rod string is developed. The fatigue safety zone obtained with this new approach is wider than that calculated with conventional methods. Hence, this new approach can give full play to the performance of sucker rods of all grades in their design, so as to optimize the combination of Grade H rod string and increase the usable length of small-diameter sucker rod. In other words, the overall weight of rod string is lowered, which reduces the load on rod string and the lateral force on rod string. In this way, tubing and sucker rod wearing is effectively slowed down.

3.4. Supporting Measures

To implement all kinds of technical measures, a classified management system is established with oil field company, oil mining plant, and operation area. Supporting Measures were shown in Table 2.
Table. 2 Main supporting techniques for protecting wellbore against lopsided wearing in oil field

| Supporting Techniques against Lopsided Wearing | Applicable Conditions | Management Requirements |
|-----------------------------------------------|-----------------------|-------------------------|
| Centralizing rod                              | Well sections or entire borehole trajectory with slight lopsided wearing | Design the number of centralizing rods reasonably while optimizing the design of rod string |
| Centralizer                                   | Local well sections with severe lopsided wearing | Strengthen the analysis of forces on rod string and the delicate description of borehole trajectory, reasonably design the position and quantity of centralizers, anti-stripping devices and bi-directional protective couplings, improve the effect of protection against wearing and lower the cost of application |
| Two-directional protective coupling            | Well sections subject to lopsided wearing below pump setting depth and neutral point | |
| Anti-stripping device                         | Oil wells with well sections subject to serious lopsided wearing or noticeable directional lopsided wearing | Study and apply the digital sucker rod pump with multifunctional rope handing device on the basis of existing technologies |
| Multifunctional rope handing device           | Oil wells subject to severe lopsided wearing or the breaking, leaking tubing, and high frequency of operation arising from lopsided wearing | Reinforce the analysis on the condition of wellbore, study and determine the application boundaries of lined tubing |
| Lined tubing                                  | Oil wells subject to severe lopsided wearing or the breaking, leaking tubing, and high frequency of operation arising from lopsided wearing | Provide the satisfying couplings and centralizers for sucker rods of small size to eliminate the problems of tubing expansion or diameter reduction |

4. Site Application

In 2017, remarkable achievements had been made after implementing the comprehensive control throughout the oil field. Compared with 2015, the oil field lowered its frequency of well maintenance operation from 0.99 to 0.85 and reduced its maintenance by more than 6,000 well times, which realized the cost saving of more than 60 million RMB. In two demonstration operation areas of the corporate level, i.e. Geng 116 and Yan 44, the frequency of maintenance operation decreased from 2.53 to 1.33 times/year • well and from 3.1 to 0.79 times/year • well respectively. Through the comprehensive control of wells subject to lopsided wearing, the frequency of well maintenance operation had been significantly lowered throughout the oil field, so as to improve the quality level of wellbores on the whole.

5. Conclusion

(1) Three-dimensional wellbore model is constructed and improved to optimize the design of protection against wearing for pipe string by utilizing the dynamic distribution law of lateral force in three dimensions, so as to provide the design method and theoretical basis for tailored control.

(2) A model is built to calculate the neutral point in the combinational pipe string of composite pipe and steel tubing, while an approach is proposed to optimize the design of centralizer, so as to realize the accurate protection against wearing for wellbore. This provides a new way to ensure the economy of protection against wearing in the context of low oil prices.

(3) By modifying the model for the calculation of allowable stress, the fatigue safety zone of ultrahigh strength sucker rod is widened to lower the overall weight of rod string and reduce the lateral force on rod string, so as to effectively extend the service life of sucker rod.

(4) Through the combination of design optimization with regulation formulation and system establishment, and the combination of technology with management, the comprehensive control of lopsided wearing in oil wells is realized to effectively lower the frequency of well maintenance operation and realize the scientific “frequency control and efficiency improvement”.

References

[1] PA Lollback, GY Wang, SS Rahman. An alternative approach to the analysis of sucker-rod dynamics in vertical and deviated wells [J], Journal of Petroleum Science & Engineering, 1997, 17 (3–4): 313-320.

[2] BX Liu, HZ Liu. Dynamic Analysis of the Sucker-Rod Pumping System of Deviated Well Based
on LuGre Friction Model [J], Advanced Materials Research, 2010, 139-141 (139-141): 2346-2349.

[3] JL Rrushi, CyberRadar. A Regression Analysis Approach to the Identification of Cyber-Physical Mappings in Process Control Systems [J], Acta Petrolei Sinica, 2011, 156 (6): 217-218.

[4] Jin Congqi, LV Shuzhang, HAN Yingsheng. Pumping well partial wear and corrosion mechanism and Prevention Countermeasures [J], OIL FIELD EQUIPMENT, 1999, 28 (5): 15-19.

[5] Wu Yanqiang, WU Xiaodong, HAN Guoqing. Prediction model of rod wear life based on partial-wear analysis [J], OIL DRILLING & PRODUCTION TECHNOLOGY, 2013 (1): 79-82.

[6] Dong Shi-min. Mechanical analysis on causes of worn rod string and tubing of rod pumping wells in the water-flooding oilfield [J], ACTA PETROL EI SINICA, 2003, 24 (4): 108-112.

[7] Han Hong-sheng, WANG De-min, GUO Li-ping. Partial abrasion mechanism of sucker rod caused by normal stress of visco-elastic fluid [J], ACTA PETROL EI SINICA, 2004, 25 (4): 92-95.

[8] Liu He, Wang Su-ling. Prediction of abraded points between sucker rod string and tubing by using finite element method [J], ACTA PETROL EI SINICA, 2008, 29 (1): 149-152.

[9] Chen Tao. Partial wear of rod tubing and Prevention [J], CORROSION & PROTECTION IN PETROCHEMICAL INDUSTRY, 2010, 27 (1): 31-32+53.

[10] Yan Qinshan, Lin Ge. Optimum design of sucker rod in d WELL [J]. Xinjiang Petroleum Science, 2007, 1 (17): 27-29.