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Analysis of Pump Efficiency and Feed Flow Under the Condition of Flexible Rate

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Abstract: In this paper, a flexible method of optimizing the velocity of plunger is presented by selecting important oil well production parameters through orthogonal test and combining the oil well parameters and the structural parameters of the pump barrel. In order to explore the influence of the motion rate of the optimized flexible plunger on the pump efficiency, the motion law curves of the plunger before and after the optimization were compared, and the pump efficiency before and after the optimization was theoretically analyzed. The flow rate and pump efficiency of the pump before and after optimization were simulated by the model. Finally, the pumping unit experimental system is used to test the pumping pump fluid production before and after optimization. The results show that the pump efficiency under the optimized flexible rate is 3.7% higher than that before the optimization without considering other factors. The model simulation analysis shows that the mass flow rate of the pump in a single swabbing period under the condition of optimized flexible rate is increased, and the pump efficiency is increased by 4.9% compared with that before optimization. The experimental results of the pumping unit experimental system show that the fluid yield under the optimized flexible rate is higher than that before the optimization, and the maximum increase is 4.1%. The experimental results are consistent with the theoretical analysis results.

Keywords: Flexible control, Orthogonal test, Optimize, Velocity of plunger motion, Pump efficiency, Model simulation.

1. Introduction

Beam pumping unit has many advantages, such as simple structure, strong adaptability, economic durability and so on. It plays a pivotal role in the field of mechanical oil recovery. So far, it is still the main tool of mechanical oil recovery in many oil fields around the world. However, due to the inherent geometric characteristics of the beam pumping unit and the circular rate driving mode (i.e., the crank does uniform circular rotation), the pumping system has many problems such as large energy consumption and low efficiency in the working process. Engineering analysis shows that the oil recovery efficiency can be improved by using flexible rate drive. Therefore, many oil fields begin to study, use and popularize the flexible control pumping technology of pumping unit gradually.

The flexible control pumping technology of pumping unit is an optimized variable speed drive technology [1-2]. Its main objective is to improve the motion process of the entire pumping system, make the oil recovery rate match the current pumping system and reservoir characteristics, so as to reduce the energy consumption of the pumping well and improve the pumping efficiency.

Most of the existing flexible pumping control technologies only focus on the optimization of the pumping speed of Pumping unit and motor frequency [3-4], instead of corresponding optimization based on downhole physical parameter conditions and pump structural parameters, and the adjustment ability and control range are limited to a certain extent. For the sake of effectively improve pump efficiency and optimize oil recovery rate of pumping unit, this paper selects key production parameters such as stroke, pumping speed and sinking degree through orthogonal test. Based on the selected production parameters, combined with the physical parameters of the well and the structural parameters of the pump barrel, the plunger speed is optimized, and the optimized flexible plunger speed curve based on specific well conditions is obtained. In order to explore the influence of the optimized flexible piston movement rate on the pump, the plunger movement laws before and after the optimization were compared under the same conditions, and the pump efficiency and flow rate of the pump were calculated and evaluated. The results can provide some guidance for the flexible control strategy of the oil pumping system.

2. Orthogonal Experimental Design

2.1. Pump efficiency and liquid production

The pumping efficiency of the pumping pump is an important parameter to reflect the pumping efficiency of the pumping well. If the pumping efficiency is high, the pumping efficiency of the pumping well is high, and the current suction parameters are reasonable. If the pump efficiency is low, the relevant parameters should be adjusted or optimized. Therefore, the pump efficiency can provide some reference for the adjustment of swabbing parameters. The main influencing factors of pump efficiency can be summarized into the following four aspects: η_S——the effective stroke coefficient of the plunger, η_F——the coefficient of the fullness degree of pump; η_L——leakage coefficient of the pump; η_V——volume coefficient of crude oil under submerged pressure. Pumping efficiency η is expressed as formula (1) :

$$\eta = \eta_S \eta_F \eta_L \eta_V \tag{1}$$

The calculation method of pump leakage coefficient ηL is shown in Equation (2), and the other influencing factors can be calculated in reference [5].

$$\eta_L = \frac{A_P S \eta_S \eta_F \eta_V - \Delta Q}{A_P S \eta_S \eta_F \eta_V} \tag{2}$$

In the equation: A_p is the cross-sectional area of the plunger of the pump, m^2;S is the stroke, m; ΔQ is the amount of fluid loss during a stroke of the plunger through the gap between the plunger and the pump barrel, m^3, its calculation formula is:

$$\Delta Q = \frac{\pi D \Delta p \delta^3}{12 \mu L_c}\left(1 + \frac{3}{2}\varepsilon^2\right) T_u \qquad (3)$$

In the equation: Δp is the pressure difference between the upper and lower plunger, Pa; δ is the mean radius clearance between the plunger and the pump barrel, m; L_c is the plunger length, m; ε is the relative eccentricity, ε=e/δ; e is the eccentricity of the center line of the plunger relative to the center line of the pump barrel, m; T_u is the time corresponding to the upper stroke of the plunger, s; μ is the dynamic viscosity of oil well fluid, Pa·s.

The formula for calculating liquid production Q is as follows:

$$Q = 1440 \times \frac{\pi}{4} D^2 \eta \qquad (4)$$

In the equation: D is the diameter of the pump, m; η is the pump effect, decimal.

2.2. Introduction to orthogonal test

Orthogonal experimental method is an efficient research design method, which is often used in multi-factor optimization. It makes use of mathematical statistics and the principle of orthogonality [6], and selects some representative points from all the tests according to the orthogonality. These representative points also have the characteristics of "evenly dispersed, neat and comparable", which can greatly reduce the number of tests and workload while ensuring the accuracy of results. In the orthogonal test, since the number of different factors of each factor is the same, and the probability of each factor combination with other different factors is equal. Therefore, by analyzing part of the test results, the situation of all the tests can be comprehensively and systematically known, and the influence degree of each factor on the target can be obtained. Finally, the optimal or better test scheme can be obtained, so as to achieve the purpose of parameter optimization.

2.3. Orthogonal test scheme and calculation

According to the measured data of Jiangsu oilfield, the main parameters of a pumping well are as follows: The pumping unit model is CYJY10-3-53HB, casing pressure is 0.4MPa, wellhead back pressure is 0.8MPa, crude oil density is 870 kg/m3, water cut is 0.68, surface gas/oil ratio of crude oil is 14 m^3/ m^3, formation temperature is 60°C, the oil well adopts three stage sucker rod. The diameter of the primary sucker rod is 25 mm. The secondary sucker rod is 22 mm. The tertiary sucker rod is 19 mm.

According to the research on the physical parameters of the well and the research and analysis of the comprehensive data of the oilfield block, the influence factors of orthogonal test are determined from four aspects: pumping stroke, stroke times, pump diameter and sinking degree. and the pump efficiency and liquid production were taken as the objective functions to carry out the orthogonal test. In order to reduce the influence between the horizontal spans of each impact factor, each impact factor was designed by means of arithmetic difference, and the orthogonal test scheme was developed, as shown in Table 1.

According to Table 1, the pump efficiency and liquid production under the corresponding parameter conditions were calculated. According to the common orthogonal test table [5]$L_{16}(4^4)$, an orthogonal test scheme with 4 factors and 4 factors was designed. A total of 16 tests were conducted, and the test results were listed in Table 2, which significantly reduced the number of comprehensive tests (4^4= 256). Improve the efficiency of calculation.

Table 2. Scheme of orthogonal test and results of numerical calculation

Test number	Each factor				Index of test	
	submergence depth	stroke	stroke times	Pump diameter	pump efficiency	liquid production (m^3/d)
1	1	1	1	1	0.21	1.73
2	1	2	2	2	0.30	5.83
3	1	3	3	3	0.37	14.20
4	1	4	4	4	0.41	27.59
5	2	1	2	3	0.32	7.04
6	2	2	1	4	0.37	6.80
7	2	3	4	2	0.47	17.26
8	2	4	3	1	0.42	10.11
9	3	1	3	4	0.33	12.16
10	3	2	4	3	0.37	15.66
11	3	3	1	2	0.35	5.14
12	3	4	2	1	0.46	8.30
13	4	1	4	2	0.34	9.55
14	4	2	3	1	0.41	7.80
15	4	3	2	4	0.38	13.73
16	4	4	1	3	0.44	9.44

The orthogonal influence test results of each influence factor are shown in Table 2. As can be seen from Table 2, with the increase of stroke, stroke times and pump diameter, pump efficiency and liquid production will be greatly improved. With the increase of sinking degree, pump efficiency will increase to a certain extent.

In order to maximize the expected pump efficiency and effectively improve the oil production efficiency of the well, parameters of the group with the highest pump efficiency (group 7) in the orthogonal experiment were selected for subsequent flexible optimization.

3. Search for Velocity Curve of Flexible Plunger

The optimization idea of this paper is to first assume the plunger movement curve, then construct the optimization objective function according to the parameters selected by orthogonal experiment, the basic parameters of the well condition and the structure of the pump, and carry out the corresponding solution calculation combined with the constraint conditions. Finally, the optimal plunger movement rate curve satisfying the conditions is obtained, which can be used for the flexible driving of the pumping unit.

3.1. Construction of flexible rate curve

In order to ensure that the expression of the optimized curve is characterized by easy solution, strong adaptability, and multiple combined solution sets, as well as a certain periodicity, the displacement equation of the pump plunger movement is assumed to be a function variable expressed by Fourier series expansion [7], as shown in Formula (5) :

$$x(t) = a_0 + \sum_{i=1}^{j}\left[a_i \sin(i\frac{2\pi t}{T}) + b_i \cos(i\frac{2\pi t}{T}) \right](j \geq 2) \tag{5}$$

In the formula: a_0, a_1, b_1, …, a_N and b_N are Fourier expansion coefficients.

Because the form of Fourier series is used to represent the equation of plunger motion, when we select appropriate optimization objectives and constraints to solve x(t) that meets the conditions, we can get the coefficients of the optimized Fourier series, namely:

$$X = \left\{ a_0, a_1, b_1, a_2, b_2, ...a_j, b_j \right\} (j \geq 2) \tag{6}$$

According to the solved coefficients, the optimized plunger motion equation can be formed, that is, the optimized flexible plunger motion rate curve can be obtained.

3.2. Optimization Objectives

Since the fullness degree of pump occupies a large part of the factors affecting the pump efficiency, and the fullness degree of pump is most affected by the plunger movement and the structural parameters of the pump, the coefficient of pump filling degree is selected as the optimization objective in order to facilitate the establishment of an appropriate formula. The coefficient of pump filling degree is expressed by β(the ratio of the volume of fluid in the suction pump, $V_L(t)$, to the volume of the up-stroke plunger, $V_S(t)$).

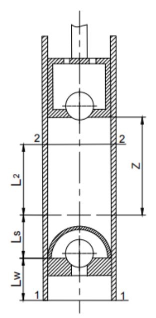


Figure 1. Schematic diagram of pump structure

(1) According to the conservation of mass and energy, Bernoulli's equation at the fluid flow section of the pump can be written:

$$\frac{p_1}{\rho_1 g} + \frac{v_1^2}{2g} = \left(L_2 + L_s + L_w\right) + \frac{p_2}{\rho_2 g} + \frac{v_2^2}{2g} + h_{1-2} + h_i \tag{7}$$

In the formula: v_1 is the flow velocity at section 1-1, m/s; v_2 is the flow velocity at section 2-2, m/s; p_1 is the pump inlet pressure, MPa; p_2 is the pressure in the pump, MPa; g is the acceleration of gravity, g= 9.8m /s^2; L_2 is the height of liquid in the pump, m; L_S is the clearance length of the oil pump, m; L_w is the length of oil pump liner, m; ρ_1 is the fluid density at section 1-1, kg/m^3; ρ_2 is the fluid density at section 2-2, kg/m^3; h_{1-2} is fluid drag and head loss, m; h_i is inertance drag and head loss, m.

(2) The liquid level height L_2 in the pump at time t can be calculated as:

$$L_2 = \int_0^{S_p} \frac{30}{\pi n} \frac{v_2(t)}{\sqrt{x(t)S_p - x(t)^2}} dx \tag{8}$$

Then, the liquid volume $V_L(t)$ in the pump at time t is:

$$V_L(t) = L_2 A_p \tag{9}$$

In the formula: $x(t)$ is the displacement of the plunger, m; n is pumping speed, min^{-1}; S_p is the effective stroke of the plunger, m; A_p is the cross-sectional area of the plunger, m^2; S_p is the effective stroke, m.

(3) Pump chamber volume $V_S(t)$ is:

$$V_S(t) = A_p x(t) + V_s \tag{10}$$

In the formula: V_s is the clearance volume of the pump, m^3.

(4) Finally get the fullness degree of pump expression as shown below:

$$\beta = \frac{V_L(t)}{V_S(t)} \tag{11}$$

Then the main optimization objective function can be expressed as:

$$F(x) = \max \beta(S, n, D, l, L_s, L_w, \rho_l, h_s, H_d, a_0, b_0, a_1, b_1, \cdots, a_N, b_N) \tag{12}$$

In the formula: S is stroke, m; n is pumping speed, min^{-1}; D is pump diameter, m^2; l is length of sucker rod, m; ρ_l is the well fluid density, kg/m^3; h_s is submergence depth, m; H_d is the depth of producing fluid level, m.

3.3. Find the solution

In order to delimit the solution range, make the optimization calculation of the curve have a more appropriate and reasonable solution domain, and achieve the purpose of improving the pump efficiency and productivity, the boundary constraint conditions are set as follows:

$$\begin{cases} G(1)=\beta_0-\beta_y<0 \\ G(2)=\eta_0-\eta_y<0 \\ G(3)=\sigma_{\max}-[\sigma_{\max}]<0 \\ G(4)=N_f-N_{fv}<0 \end{cases} \quad (13)$$

In the formula: β_0 and β_v are the fullness degree of pump before and after optimization; η_0, η_v are the pump efficiency before and after optimization; σ_{max} is the maximum working stress of the sucker rod, MPa; $[\sigma_{max}]$ is the maximum allowable stress of the sucker rod, MPa; N_f and N_{fv} are the number of stress cycles before rod failure before and after optimization.

Based on the objective function and constraint conditions established above, the mathematical model of optimization design of the plunger motion curve can be established as follows:

$$\begin{cases} F(x)=\max \beta(S,n,D,l,L_s,L_w,\rho_l,h_s,H_d,a_0,b_0,a_1,b_1,\cdots,a_N,b_N) \\ G(i)<0 \quad i=1,2,3,4 \end{cases} \quad (14)$$

The variable value of optimization solution is:

$$X=\{a_0,a_1,b_1,a_2,b_2,...a_j,b_j\}(j\geq 2) \quad (15)$$

In summary, the optimization process is as follows: according to the main optimization objective function and constraint conditions (14), the solution algorithm is used to obtain the optimal variable value in (15) under the condition of specific well condition parameters, so as to obtain the optimal flexible plunger motion curve equation expressed by Fourier series under the condition of the specific well condition parameters.

The above optimization problem is actually a nonlinear optimization problem of discrete variables, and the actual solving process is relatively complex, considering the efficiency and global nature of genetic algorithm, genetic algorithm is adopted here to solve the optimization model.

4. Plunger Movement Law Analysis

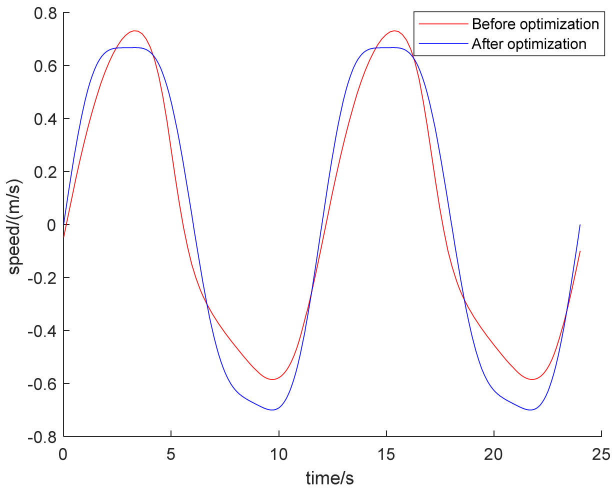
Based on the measured well condition data parameters of Jiangsu oilfield, parameters such as stroke and submergence depth obtained by orthogonal experiment and corresponding constraint conditions, the optimal Fourier series coefficients are obtained as follows:

$a_0=1.3572$, $a_1=-0.1728$, $b_1=-1.3482$, $a_2=0$, $b_2=-0.0072$

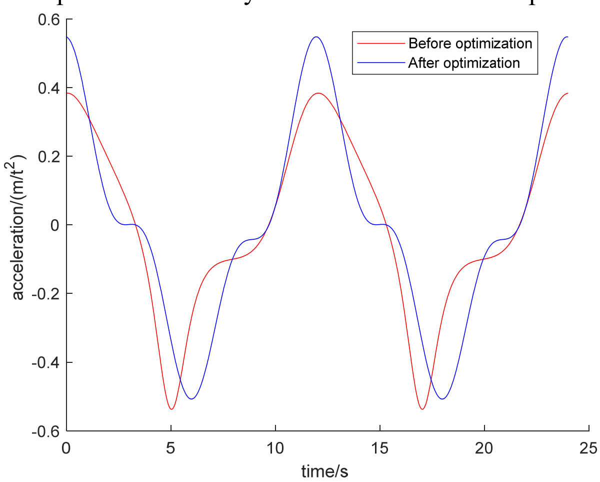
Therefore, the optimal flexible plunger motion rate curve is finally obtained as follows:

$$x(t)=1.3572-0.1728\sin\left(\frac{2\pi t}{20}\right)-1.3482\cos\left(\frac{2\pi t}{20}\right)-0.0072\cos\left(2\cdot\frac{2\pi t}{20}\right)$$

Compare the speed and acceleration characteristics of the plunger before and after optimization, as shown in Figure 2:



a. Comparison of velocity curves before and after optimization



b. Comparison of acceleration curves before and after optimization

Figure 2. Comparison of plunger velocity and acceleration before and after optimization

As can be seen from the figure, compared with the plunger motion curve before optimization, the optimized plunger motion curve has a higher speed at the initial up stroke, which is conducive to the rapid change of pressure in the pump and the rapid inflow of liquid into the pump. However, the speed change at the maximum speed is more stable. At the same time, the speed at the maximum speed of down stroke is larger and more stable, which ensures the smooth and rapid discharge of liquid.

According to the well parameters, formula (1) calculated that the pump efficiency before optimization was 47% and the pump efficiency after optimization was 50.7%. Therefore, the optimized flexible rate can improve pump efficiency by 3.7% at this well parameter.

5. Simulation Analysis of Pump Based on Finite Element Software

Compared with the plunger velocity before optimization, the plunger movement law of the pump has changed to some extent. Different plunger velocities in a pumping cycle will lead to different fluid velocity variation laws in the pump, which will have a certain degree of influence on the fluid production. The internal flow field of the pump and the flow rate of the pump were studied by using the finite element software. Due to the complex structure of the pump, it is difficult to realize the modeling calculation completely according to the actual model. Therefore, the following basic assumptions are made: (1) The bottom pump valve orifice is simplified as the speed inlet, without considering the valve housing; (2) The upper end is the exit boundary. (3) There is no gap between the plunger and the pump chamber, and the leakage between the plunger and the pump chamber is not considered [8]; The model is shown in Figure 3:

Figure 3. Simplified model of pump

According to the flow state of bottomhole fluid entering the pump barrel of the pump, the simulation model is set as follows: the round ball in Figure 3 represents the valve ball, and the rest are the wall of the pump; The flow model of the fluid in the pump is set as turbulence model. The bottom end is the fluid inlet, which is set as the velocity inlet boundary; the top end is the fluid outlet, which is set as the pressure outlet boundary; the rest part is set as the wall boundary. The temperature field of the whole simulation model is set as constant, the simulated fluid is an oil-water mixture with a density of 870 kg/m^3, the viscosity coefficient is 0.24, the pump inlet pressure is 3 MPa, the pump outlet pressure is 12 MPa. The finite element software was used to analyze the flow field of pump and the flow rate of the incoming pump before and after the optimization, and the cloud diagram of the flow rate change in the pump at some time (as shown in Figure 4), the flow of fluid into the pump and the pump efficiency (as shown in Table 3) were obtained.

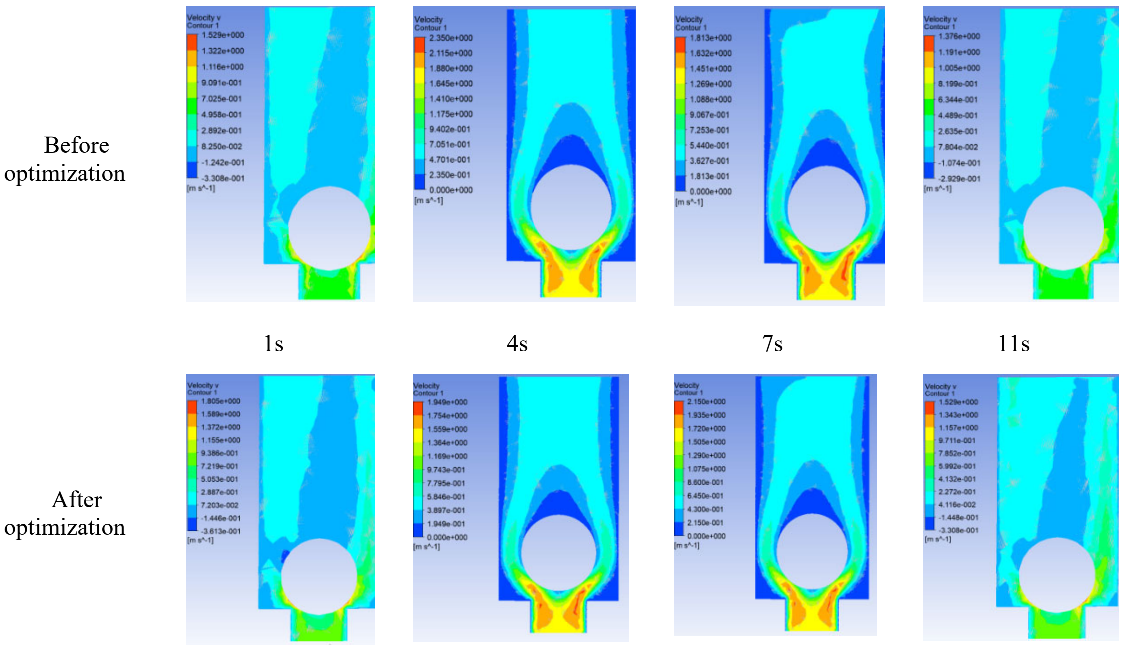


Figure 4. Cloud diagram of velocity variation in plunger at partial time

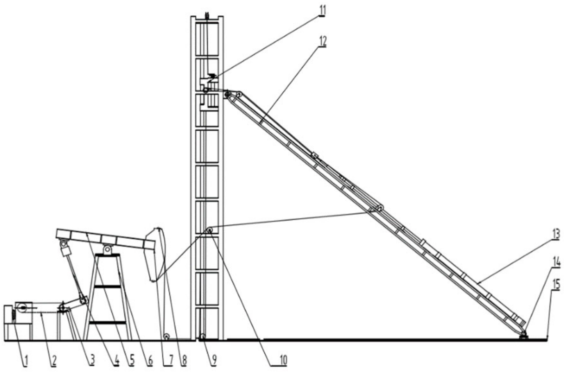
Table 3. Inlet pump flow and pump efficiency before and after optimization

	Mass of incoming pump fluid during a swabbing cycle (g)	pump efficiency (%)
Before optimization	1630	43.6
After optimization	1782	48.5
Range of optimization	9.3%	4.9%

It can be seen from the results that under the condition that the stroke, stroke times and other parameters are the same and only the plunger movement law is changed, after optimization, the flow rate of the incoming pump increases in a single swabbing cycle, and the pump efficiency increases by 4.9%. Therefore, the liquid production is higher under the flexible rate condition.

6. Test and Data Analysis

According to the basic working parameters, a 1∶4 pumping unit test system is set up to simulate the working process of the whole pumping unit under the condition of two kinds of piston speed before and after optimization(According to the optimized flexible plunger speed curve *x(t)*, the motion rate of the suspension point of the pumping unit can be inversely derived, and then the motor speed can be inversely derived from the motion rate of the suspension point of the pumping unit. By adjusting the frequency conversion motor speed to the motor speed obtained by the above inverse push, the pumping unit experiment system device can simulate the working process of the whole pumping system under optimized conditions). The device is mainly composed of variable speed drive system, Support system and oil pumping system. The schematic diagram of the test device is shown in Figure 5:



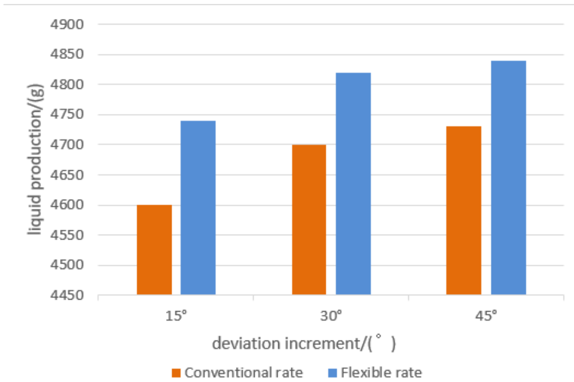
1. Variable frequency motor 2. Support mechanism 3. Crank 4. Connecting rod 5. Walking beam 6. support frame 7. Horsehead 8. Capstan 9. fixed pulley 10. friction pulley 11. Vertical moving device 12. Support frame 13. Oil pumping pump 14. Horizontal moving device 15. Bottom guide rail

Figure 5. Pumping unit test system structure

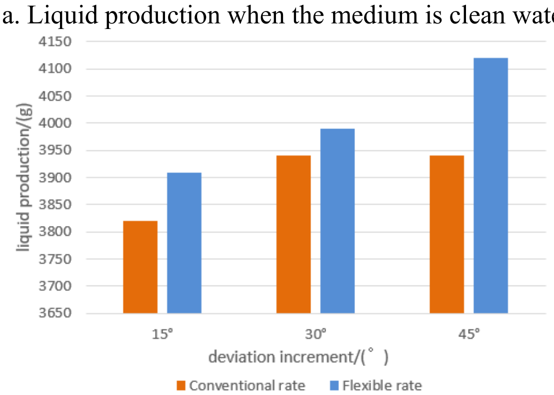
The solid diagram of the test device is as follows:

Figure 6. Pumping unit test system device

The test period of the experiment was 1min, and the experimental medium was clean water and oil-water mixed solution, respectively. The fluid production of the pumping system was tested under the conditions of two kinds of plunger movement rates before and after optimization when the borehole deviation was 15°, 30° and 45°, respectively. The experimental results are shown in Figure 7:



a. Liquid production when the medium is clean water



b. Liquid production when the medium is oil-water mixture

Figure 7. Comparison of experimental results

As can be seen from Figure 7, when the experimental medium is clean water and oil-water mixture, the liquid production after optimization is increased to a certain extent compared with that before optimization, and the maximum increase is 4.1%. Therefore, under the condition that the test error is excluded, the law obtained by the test experiment is consistent with the theoretical calculation results, and the optimized flexible plunger rate can effectively improve the fluid production of the well to a certain extent.

7. Conclusion

(1) Considering the well condition parameters and the structure parameters of the pump comprehensively, the motion model of the flexible plunger of the pump was established with the filling coefficient of the pump as the main optimization objective, and the optimized rate curve of the flexible plunger was found.

(2) When other factors are not considered, the theoretical analysis and calculation show that the pump efficiency under the optimized flexible rate condition is improved, and the pump efficiency is 3.7% higher than that before optimization. The simulation model was established to analyze the inlet flow rate and pump efficiency of the pump before and after optimization. It can be seen that the mass flow rate of the inlet fluid increased within a single swabbing cycle of the flexible rate curve after optimization, and the pump efficiency increased by 4.9%.

(3) The test results of the pumping unit test system show that liquid production after the flexible rate optimization is higher than that before the optimization, with the maximum increase of 4.1%, which is consistent with the results of theoretical analysis.

(4) The optimized flexible plunger rate can effectively improve the pump efficiency and liquid production, and the conclusions can provide certain guidance for the flexible operation control strategy of the pumping system.

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