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Research on Production Operation System of Sucker Rod Pumping Units

Shaonan Wang, Yang Qiao, Jianjian Fan, Qingfeng Zhou

Xi'an Shiyou University, Xi'an Shaanxi 710065, China

Abstract: Oil is the most important raw material in modern industry, and its extraction mainly relies on natural flow and artificial lifting. Sucker rod pumping is currently the most widely used method of artificial lifting for mechanical oil extraction, accounting for about 60% to 70% of all methods. This paper deeply explores the theoretical methods involved in the production operation process of sucker rod pumping units. From the perspective of sucker rod pumping unit production operation, a literature review is conducted on the flow patterns in the wellbore, pump efficiency analysis, and intermittent oil extraction systems, clarifying the optimization objectives of liquid production and system efficiency, and sorting out from the aspects of dynamic liquid level, pump efficiency, reasonable submergence depth, and intermittent operation systems. Through in-depth analysis of these key areas, a solid methodological foundation is provided for the future design and development of sucker rod pumping unit production operation systems.

Keywords: Dynamic Liquid Level; Pump Efficiency; Submergence Depth; Intermittent Oil Production.

1. Introduction

Oil is the 'lifeblood' of modern industry, playing an extremely important role in the development of our country's economy. There are two methods of oil extraction: one is the natural flow of oil, known as primary oil recovery, and the other is artificial lifting, which includes various mechanical methods. The sucker-rod pump, also known as the beam pump, is currently the most widely used method of artificial lifting, accounting for approximately 60% to 70% of all methods. Traditional production operations of the pumping unit often rely on manual experience and fixed working systems, requiring oilfield personnel to have extensive knowledge, accumulated experience, and relevant parameter indicators. When production efficiency issues arise, they must make comprehensive judgments, accurately analyze various aspects of the pumping unit's operation to identify the causes of the problem, and thus make scientific and reasonable decisions quickly to optimize the working system of the pumping well. This paper conducts a literature review from the perspective of sucker-rod pumping unit operation, focusing on the flow pattern in the wellbore, pump efficiency analysis, and intermittent oil extraction systems. It clarifies the optimization goals of liquid production and system efficiency, and organizes factors such as the dynamic liquid level, pump efficiency, reasonable submergence depth, and intermittent operation systems. Through in-depth analysis of these key areas, it provides a solid methodological foundation for the design and development of future sucker-rod pumping unit operation systems.

2. Research on the Dynamic Liquid Level in the Wellbore

Accurately determining the dynamic liquid level in oil wells is crucial for estimating the depth of oil and gas fluids and for formulating oil well production plans. The measurement of the dynamic liquid level can be achieved through physical measurement, soft measurement, or ultrasonic detection. Physical measurement mainly includes the float method [1][2] and the pressure gauge detection method. This method requires high equipment specifications and is less accurate, hence it is less commonly used. Soft measurement involves collecting performance graph data or constructing mathematical models to analyze and estimate the dynamic liquid level. It has the advantages of low cost and high efficiency, but its popularity still needs to be increased. Ultrasonic detection uses echo signals to determine the depth of the liquid level, and it has become a research hotspot due to its low cost and wide application. Oil fields should choose the appropriate measurement method based on their geological and production conditions. The following are some widely used and more advanced calculation methods.

2.1. Echo Method

Echo method utilizes an ultrasonic pulse generator at the wellhead to release pulse sound waves that travel along the annular space of the casing. When these sound waves encounter obstacles such as echo markers or fluid interfaces, the pulses reflect back to the wellhead. By studying the signals, the fluid interfaces can be effectively identified. This method is divided into the echo marker method and the coupling method [3], depending on whether echo markers are installed.

Based on the principle that the ratio of the liquid level depth to the echo marker depth is equal to the ratio of their respective ultrasonic wave propagation times, the actual depth of the liquid level can be calculated once the accurate depth of the echo marker is determined. The calculation formula is:

$$H_d = \frac{D_s L_e}{L_s} \tag{1}$$

In the formula: H_d— Dynamic liquid level depth, m; D_s — Distance from the echo marker to the wellhead, m; L_e— The distance on the recording paper from the wellhead wave to the liquid surface wave recorded by the electromagnetic pen, m; L_s— The distance on the recording paper from the wellhead pulse wave to the echo marker wave recorded by the electromagnetic pen, m.

In the case where there are no echo markers in the pumping well or the markers have been submerged by the liquid level, the casing coupling can be used to measure the liquid depth. When the casing specifications are relatively standard, using the coupling method to calculate the liquid depth is more accurate. The calculation formula is:

$$H_d = \frac{LL_2}{L_1} \tag{2}$$

In the formula: L_1 — The length of the casing coupling wave recorded on the curve, m; L — The actual length of the casing corresponding to the L_1 curve; L_2 — The length of the pulse reflection wave on the recording curve, m.

2.2. Pump Work Diagram Calculation Method

The downhole pump, due to its relatively simple force structure and less affected by dynamic loads, can obtain all required calculation parameters in real time. By using the work graph data collected on the ground, the pump work graph can be effectively calculated by solving the one-dimensional damped wave equation. Based on the pump work graph method, the actual depth of the dynamic liquid level can be calculated [4], and the calculation formula is:

$$H_d = \frac{F_{pu}-F_{pd}}{\rho_o g A_p} + \frac{p_c-p_n-2\Delta p}{\rho_o g} + \left(1-\frac{\rho_l}{\rho_o}\right)L - \frac{2f}{\rho_o g A_p} \tag{3}$$

In the formula: F_{pu} — Average load during the upstroke, N; F_{pd} — Average load during the downstroke, N; ρ_o — Density of crude oil, kg/m³; g — Acceleration due to gravity, m/s²; A_p — Plunger cross-sectional area, m²; p_c — Casing pressure at the wellhead, Pa; p_n — Submergence pressure, Pa; Δp — Pressure drop across the valve, Pa; ρ_l — Density of the fluid in the wellbore, kg/m³; L — Length of the sucker rod, m; f — Frictional force between the plunger and the pump barrel, N.

2.3. Electrical Work Graph Calculation Method

During the sucker-rod pumping process, the work done by the suspended point load is closely related to the variation of the dynamic liquid level, which affects energy consumption [5]. The electrical work graph calculation method is based on the direct proportionality relationship between the lifting work of the oil well and the lifting stroke, and excludes external factors by constructing a mathematical model [6]. This method defines the minimum lifting work ($E_{\min}$, the work done by the pumping unit during the upstroke when the dynamic liquid level is at the entrance of the sucker-rod pump, in kilowatts (kW) and the maximum lifting work (E_{max}, the work done by the pumping unit during the upstroke when the dynamic liquid level is at the wellhead, in kW), and calculates the work for these two extreme conditions using actual measured data [7].

$$E_{min} = \frac{L_1 \times E_{u2} - L_2 \times E_{u1}}{L_1 - L_2} \tag{4}$$

$$E_{max} = \frac{(L_p-L_1)E_{u2}-(L_p-L_2)E_{u1}}{L_1-L_2} \tag{5}$$

In the formula: L_1, L_2 — Measured dynamic liquid level depth, m; E_{u1}, E_{u2} — Corresponding measured lifting work during the upstroke for the dynamic liquid level, kW; L_p — Pump setting depth, m.

Assuming that the surface equipment configuration is fixed, the downhole production fluid medium is constant, and all production parameters are stable, the calculation formula for the current dynamic liquid level can be obtained as:

$$H_d = H_p \times \frac{E_u - E_{min}}{E_{max} - E_{min}} \tag{6}$$

In the formula: E_u — Current lifting work during the upstroke, kW.

This method has several limiting conditions. To ensure the accuracy of the calculation results and their practical application value, it is necessary to promptly re-collect the dynamic liquid level and lifting work parameters for updating in cases such as changes in the oil well injection and production conditions, rework of the oil well, or significant adjustments in production parameters.

3. Pump Efficiency Analysis

Rationalizing the operating system of the pumping unit requires that the reservoir supply is adapted to the pumping capacity of the pump, and pump efficiency analysis is key. Pump efficiency is assessed by comparing actual production (Q) with theoretical production (Q_t), which evaluates the performance of the pump and the suitability of the pumping parameters, and is an important standard for measuring equipment efficiency and management level.

Pump efficiency (η) refers to the ratio of actual production (Q) to theoretical production (Q_t) during the production process of the pumping well. The actual pump displacement is usually lower than the theoretical value, and it is only when the reservoir energy is sufficient and the well has the ability to flow naturally that the pump efficiency may exceed 1, which is very rare. In routine oilfield production, a pump efficiency of 0.6-0.7 or higher indicates good pump operation, but the pump efficiency of most wells is often less than 0.7, and some wells may be far below 0.3.

Key factors affecting pump efficiency [8][9]: First, the sucker rod and tubing undergo elastic deformation under cyclic loading, which affects the effective stroke of the plunger and reduces the volume of discharged liquid; second, if the pump chamber intakes a mixture of gas and liquid or the reservoir supply is insufficient, it will affect the flow of liquid into the pump chamber; in addition, gaps within the pump and wear of components may lead to a decrease in flow, and the pump body may be damaged by corrosion and sand particles during long-term operation, affecting the stability and efficiency of the pump; finally, due to the action of reservoir pressure, gas is compressed into the fluid during the pumping process, and crude oil will shrink in volume after being lifted to the ground due to degassing, which also affects the calculation of pump efficiency.

To improve pump efficiency in oilfield production, the following measures can be taken [10]: Select reasonable pumping parameters, for wells with low production and poor efficiency, usually choose long stroke, low stroke frequency, and smaller pump diameter configurations to reduce stroke loss and gas influence; reduce leakage impact by enhancing the wear resistance of the pump, optimizing the structure, and developing sand and blockage prevention measures, and regularly inspecting and maintaining to keep the pump in normal working condition; use necessary downhole tools, such as tubing markers, sand screens, gas separators, and sucker rod stabilizers, and other auxiliary tools; determine a reasonable submergence depth [11][12] to avoid insufficient supply or reduced pump efficiency, while also preventing equipment damage.

Tan Duohong [13], by fitting data from 234 oil wells, utilized the curve fitting method and found that the relationship curve between pump efficiency and submergence depth conforms to the shape of an exponential function, deriving an empirical relationship formula between pump efficiency and submergence depth:

$$\eta = ae^{\frac{b}{h}} \tag{7}$$

In the formula: a and b are fitting coefficients.

When calculating the reasonable submergence depth, the oilfield needs to perform parameter fitting on the empirical relationship formula for pump efficiency and submergence depth under different water cut conditions. After determining the values of parameters a and b, they are substituted into the expression for calculating the reasonable submergence depth:

$$h_s = \frac{bk+\sqrt{b^2k^2-4khb}}{2k} \tag{8}$$

Where:

$$k = \frac{[(1-f_w)\rho_o+f_w\rho_w]\times g\times Q_L}{86400P_d} \tag{9}$$

In the formula: h_s — Reasonable submergence depth, m; k — Comprehensive coefficient of the electric motor; f_w — Water cut of the oil well fluid, %; ρ_o — Density of crude oil, t/m³; ρ_w — Density of formation water, t/m³; g — Acceleration due to gravity, m/s²; Q_L — Theoretical liquid production, m³/d; P_d — Output power of the electric motor, kW.

This method requires determining the coefficients through parameter fitting of the pump efficiency and submergence depth data of the sucker-rod pump. If fitting conditions are not met, parameters can be selected based on the fitting results in the aforementioned literature (wells with less than 80% water were $\eta = 71.0e^{(-21.5/h)}$, and wells with less than 80% were $\eta = 45.1e^{(-6.2/h)}$ and then the index calculation is performed to determine the reasonable submergence depth.

4. Dynamic Analysis of Well Production Operations

In the process of pumping unit production operation, pumping unit production operation condition is good you need to analyze the pump condition, production and system efficiency parameters, and the pumping unit production operation parameters, reasonable pump depth to make dynamic adjustment, so as to optimize the working system.

4.1. Surface Dynamometer Chart Analysis

The surface dynamometer chart of a pumping unit is a graphical tool used in oilfield production to analyze and diagnose the working condition of the sucker-rod pump. It records the trajectory of the load at the polished rod's suspension point as it varies with displacement, and the closed curve drawn on a coordinate system with the horizontal axis as the suspension point displacement and the vertical axis as the suspension point load reflects the power transmission and work efficiency of the pump during the pumping unit's stroke. The theoretical dynamometer chart is approximately a parallelogram, as shown in Figure 1, and its area represents the work done in one pumping cycle. The four vertices of ABCD respectively reflect the working condition of the pump at the lower dead center, the working condition of the discharge valve, the working condition of the pump during the upstroke, and the working condition of the fixed valve. Various factors can affect and manifest on the dynamometer chart; for example, Figure 2 shows a dynamometer chart affected by gas, which is noticeably different from the theoretical dynamometer chart. Therefore, analyzing the dynamometer chart can effectively determine the production condition of the pumping well [14].

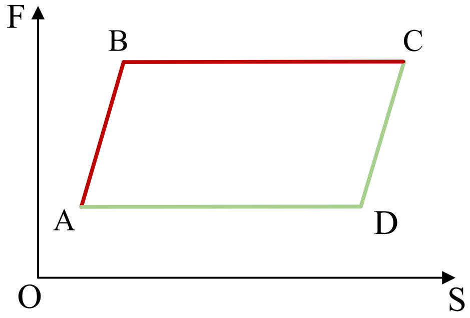

Fig 1. Represents the theoretical dynamometer chart

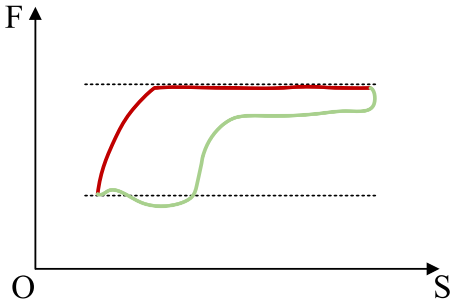

Fig 2. Illustrates the dynamometer chart affected by gas influence.

4.2. Calculation of Single Well Liquid Volume

The liquid production rate of an oilfield is an important metric for measuring the production efficiency, economic benefits, and determining the rationality of the working system of the oilfield. The calculation of liquid production can be done through pump efficiency or by using the effective stroke from the dynamometer chart [15].

The formula for calculating the actual liquid production rate through pump efficiency is:

$$Q = 1440\eta f_p sn \tag{10}$$

In the formula: f_p — Plunger cross-sectional area, m²; s — Poled rod stroke, m; n — Stroke frequency, min⁻¹.

The effective stroke method includes two approaches: the pump dynamometer chart and the surface dynamometer chart. The pump dynamometer chart effective stroke method utilizes the measured surface dynamometer chart to deduce the downhole pump dynamometer chart, and then calculates the effective stroke of the downhole pump, which is then combined with the theoretical displacement to calculate the oil well production. The surface dynamometer chart effective stroke method directly uses the measured dynamometer chart to obtain the effective stroke of the dynamometer chart, and then combines it with the theoretical displacement to determine the production. The effective stroke method takes into account the actual work efficiency of the pump, thus providing a more accurate result. The calculation formula is:

$$Q = 1440 f_p s_{pe} n \tag{11}$$

In the formula: S_{pe}— Effective plunger stroke.

4.3. Calculation of Well System Efficiency

System efficiency is also an important basis for measuring the economic benefits of the pumping unit and determining the rationality of the working system. The level of system efficiency directly affects the energy consumption and production costs of the oilfield. It reflects the degree of energy transmission and motor energy consumption of the pumping unit. The system efficiency of the pumping unit (η) is defined as the ratio of the input power to the effective power of the pumping well [16]. The calculation formula is:

$$\eta = \frac{QH\rho g}{86400 P_{\text{in}}} + \frac{Q(P_t - P_c)}{86.4 P_{\text{in}}} \tag{12}$$

In the formula:Q — Liquid production rate of the oil well, m^3/d; H — Dynamic liquid level depth, m; ρ— Density of the wellbore mixture, kg/m^3; g— Acceleration due to gravity, m/s^2; P_{in} — Input power, kW; P_t— Oil pressure, MPa; P_c — Casing pressure, MPa.

5. Research on Intermittent Oil Production System

For low-yielding oil wells with insufficient reservoir productivity and fluid supply capacity, the intermittent production system can significantly enhance pump efficiency, prevent dry pumping, and reduce energy consumption and equipment wear. This technique takes advantage of the rise in reservoir pressure during the well shut-in period, with the reservoir continuously supplying fluid to the wellbore, increasing the submergence depth of the pump, thereby enhancing pump efficiency and system efficiency. In times of declining reservoir fluid supply capacity and falling dynamic liquid levels, timely cessation of production and waiting for the liquid level to rebound to an appropriate level is a crucial part of the intermittent oil production system [17] [18].

5.1. Determination of Intermittent Well Production

Determining the on-off well timing for intermittent production first requires establishing the production rate of the interval (oil-water two-phase) being intermittently produced [19]. The production is primarily composed of two parts: first, the wellbore's continuing liquid flow rate after well shut-in (q_1), and second, the reservoir's supplied liquid flow rate after well start-up(q_2).

5.1.1. Post-shut-in Wellbore Continuing Liquid Flow Rate

To understand the supply capacity of the target formation, according to well test theory, the change in bottomhole flowing pressure after shut-in can be translated into liquid level changes, and the bottomhole flowing pressure includes the submerged pressure at the pump intake and the pressure of the mixed liquid column below the pump intake. The volume of liquid stored in the wellbore can be calculated using the bottomhole flowing pressure formula:

$$q_1 = 0.7854 \Delta H \times \left(D_t^2 - D_y^2\right) \tag{13}$$

Where the liquid level recovery height is:

$$\Delta H = \left[\frac{\rho_o \rho_w}{\rho_w + f_w(\rho_o - \rho_w)}(H_z - H_d - H_c) + H_c \rho_b\right] \frac{1}{\rho_2} \tag{14}$$

In the formula: D_t — Casing inner diameter, mm; D_y — Tubing outer diameter, mm;ρ_o — Relative density of crude oil in the mixed liquid column, t/m^3; ρ_w — Relative density of water in the mixed liquid column, t/m^3; f_w — Rate of water content; H_z — Depth of the middle of the oil layer, m; H_d — Dynamic liquid level, m; H_c — Submergence depth, m; ρ_2 — Average density of the oil-water mixed liquid column above and below the pump intake, g/cm^3.

5.1.2. Post-start-up Reservoir Liquid Supply Rate

When the oil well is shut in for a period of Δt hours and then starts up for continuous production for T hours, the liquid supply rate from the reservoir to the wellbore can be calculated based on the actual daily production rate q_x during test oiling or well testing, using the following formula:

$$q_2 = \frac{q_x}{24} \times T \tag{15}$$

5.1.3. Liquid Production of the Reservoir in One Intermittent Production Cycle

From equations (13) and (15), it can be seen that the liquid production of the reservoir in one cycle of shutting in for Δt hours and continuous production for T hours is:

$$q = q_1 + q_2 = 0.7854 \Delta H \times \left(D_t^2 - D_y^2\right) + \frac{q_x}{24} \times T \tag{16}$$

According to the actual on-off well times in one cycle of intermittent production, the daily production rate at different stages can be calculated using equations (13), (15), and (16).

5.2. Determination of Well On-Off Timing

5.2.1. Determination of the Well Opening Time

Based on the above derivation, if the pump efficiency of the oil well is known, then the well opening time can be calculated as:

$$T = \frac{0.0524 \Delta H \times \left(D_t^2 - D_y^2\right)}{\pi D^2 S_m N \eta_o - q_x} \tag{17}$$

In the formula: D — Pump diameter, mm; S_m — Stroke length, in meters (m); N — Stroke count per minute, min^{-1}.

5.2.2. Determination of the Well Shut-In Time

The daily production of the oil well and the wellbore continuing liquid flow can be approximated by the relationship between q_1 and q_x [20]. The change in bottomhole flowing pressure after shutting in for a period of Δt can be approximated as:

$$\Delta P_{wf} = P_{wf} - P_{ws} = \frac{q_x - q_1}{q_x} m \left(\lg \frac{2.25 \eta \Delta t}{r_w^2} + 0.869 S\right) \tag{18}$$

In the formula: m — Horner plot slope, Mpa/cycle, $m = 2.121 \times 10^{-3} \frac{q_x \mu B}{Kh}$; η — Conductivity coefficient, $\mu m^2 \cdot \frac{Mpa}{mPa \cdot s}$; S — Skin factor; r_w — Wellbore radius, m; K — Effective permeability of the reservoir, μm^2 ; h — Effective thickness of the oil layer, m; B — Fluid volume factor; μ — Fluid viscosity, mPa·s.

5.2.3. Post-shut-in Liquid Column Height Change

The bottomhole pressure is converted to liquid level height change using Equation (13):

$$\Delta H = \frac{q_1}{0.7854\left(D_t^2 - D_y^2\right)} \tag{19}$$

Combining equations (18) and (19), the shut-in time can be determined as:

$$\Delta t = \frac{r_w^2}{2.25\eta} \exp\left(\frac{\Delta H \rho_2 g q_x}{(q_x - q_1)m} - 0.869S\right) \tag{20}$$

6. Conclusion

This paper has organized the key research topics in the production operation of the sucker-rod pumping system and extracted the most widely used methods in oilfields currently. The normal operation of the pumping unit is the primary task of oil and gas field development. At present, the normal operation of the pumping unit heavily relies on human experience and fixed systems, which requires staff to have extensive knowledge and experience. This, to some extent, restricts the efficiency of oilfield development. Intelligentization is the trend of future social development, and the development of intelligent oil extraction systems can largely compensate for the shortcomings of traditional oil extraction. The in-depth analysis of these key areas in this paper can provide a solid methodological foundation for the design and development of sucker-rod pumping unit production operation systems.

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