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Numerical modeling of the operation of oil wells in deep pumping

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ABSTRACT: *The design and modeling of deep pumping wells are essential to ensuring the efficiency and sustainability of crude oil extraction operations. These processes are fundamental to optimizing operational parameters, reducing costs, and preventing mechanical problems that could lead to costly downtime. In the context of the continuous increase in global energy demand, the oil industry faces increasing challenges related to the exploration and exploitation of hydrocarbon deposits. To meet these challenges, engineers and operators in the field rely on advanced modeling and simulation technologies that allow them to understand better and control the complex processes involved in crude oil extraction. In this paper is presenting a new strategy of oil pumping mathematical modeling.*

KEYWORDS – *oil, deep pumping wells, models,*

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I. INTRODUCTION

In the 1960s, S. Gibbs [1] made a significant contribution to the field by developing a mathematical model of the rod assembly using the wave equation. This method, which allowed the propagation of the measured surface loads to predict the behavior of the bottom pump, has since been refined and integrated into advanced software, revolutionizing the diagnosis and optimization of pumping operations.

Current dynamometer and simulation software technology has evolved significantly, providing engineers with accurate tools for measuring and analyzing load and position data. These technologies allow for the accurate modeling of the probes' behavior and the prediction of the loads along the entire rod liner to the pump.

Importance of modeling and simulation in pumping well design consist in:

a. **Performance analysis and optimization**: Numerical modeling allows detailed evaluation of the behavior of wells under various operating conditions. Engineers can test and compare multiple scenarios through computer simulations, identifying configurations that maximize production and minimize equipment wear and tear. This systematic approach helps to determine the most effective operating parameters, thus helping to improve the overall performance of wells.
b. **Reduction of operational costs**: Optimizing operating parameters increases operational efficiency and contributes to cost reduction. By precisely adjusting pumping speed, stroke length, and piston diameter, energy consumption can be reduced, and equipment life can be extended. Thus, costs associated with maintenance and component replacement are minimized.
c. **Prevention and management of problems**: Engineers, through their proactive use of computer simulations, can identify and anticipate potential problems before they occur in reality. By testing different operational scenarios, they can detect system weaknesses and implement preventive measures to avoid major failures. This proactive approach is essential to prevent costly outages and maintain a steady flow of production.

By integrating advanced modeling and optimized design techniques, the oil industry can benefit from several significant advantages:

1. Innovative solutions:

a. Development of efficient technologies: Numerical modeling and computer simulations allow engineers to develop new and more efficient technologies for deepwater pumping. These innovative technologies can include advanced pump designs, new equipment materials, and automated control methods, all of which help improve the performance and reliability of pumping systems.

b.ImplementingImplementation cutting-edge technologies**:** By integrating the latest findings in engineering and materials science, the industry can adopt cutting-edge technological solutions that significantly improve the extraction process. These solutions can lead to more efficient and economical extraction of hydrocarbons, thereby reducing costs and maximizing production.

2. Improving operational performance:

a.Proactive problem identification**:** Advanced modeling and simulations are crucial in identifying potential problems before they manifest in real operations. This proactive approach, coupled with the Implementation of advanced technical solutions, significantly reduces the downtime of wells, ensuring continuous and efficient operation.

b. Efficient maintenance planning: Advanced diagnostic and monitoring technologies play a key role in planning and executing maintenance more efficiently. This includes identifying component wear before it leads to major failures and implementing a predictive maintenance program that reduces costs and prevents unexpected downtime.

3. Environmental Protection:

a.Minimize losses and waste: More efficient and safer pumping systems developed through advanced modeling help reduce accidental losses and waste produced during the extraction process. This is essential to protecting the environment and complying with strict environmental regulations.

b.Reduction of ecological impact: The oil industry can reduce its negative impact on the environment by optimizing pumping operations and using equipment with low emissions. Advanced technologies enable more efficient resource management and Reduction of the carbon footprint of extraction operations.

II. CALCULATION OF DANGEROUS AND NON-DANGEROUS FREQUENCIES OF OIL PUMPING DEEP WELLS

When the piston takes the weight of the liquid column and, thus, the rod seal is stretched throughout the upward stroke like a spring called upon to stretch.

At the beginning of the downward stroke, the pipes play a crucial role by taking over the entire weight of the liquid, thereby relieving the seal from the stretching force. This underscores the importance of each component in the pumping system and its specific function $\lambda = 4L$.

Vibrational phenomena explain some anomalies of the dynamograms and some breakages of the pumping rods. The maximum value of the vibratory phenomenon is at the piston.

When the piston reaches the lowest level, under the influence of its free oscillations, the liquid column takes these oscillations in its mass. It should be specified that these oscillations are primed over time due to the friction between the pipes and the rods.

It's our responsibility to prevent synchronism phenomena.

If the free oscillations caused by the spring are added to the forced oscillations caused by the movement of the balance head, fulfilling the condition that the two oscillations are equal, or multiples of each other, and in phase agreement, phenomena of synchronism are produced.

These oscillations strengthen each other and can lead to the breaking of the pump rod seal. This is why it's necessary to establish a number of strokes on the polished rod, so that these synchronism phenomena do not occur.

This recommended number of strokes can be established using a chart or the analytical calculation below:

$$n_i = \frac{76500}{N_i \cdot L} \tag{1}$$

$$n_I = \sqrt{n_i \cdot n_{i+1}} \tag{2}$$

where:

- n_I - dangerous frequencies,
- n_i - non-dangerous frequencies,
- N - the ratio of the frequencies of free and forced oscillations (N = 1..6)
- L - pump mounting depth

Following the calculations, the frequency immediately higher than the minimum frequency given by is chosen current well installation.

The choice of the pump and the pumping unit is made for economic reasons aiming at a redesign of the operating regime, with the preservation of the existing pumping unit at the well and with the current pump. Only the rod and extraction pipe assembly is resized.

The pumps used are P $2^{3/8}$ x $1^{1/4}$ type.

The surface stroke of the piston and the number of strokes (Analytical calculation of the actual stroke of the piston) is made according to the area of the piston of the pump, A_{pist}, and the efficiency of the installation α, which depends on the mounting depth of the pump:

- for H > 2500 m, α = 0.5..0.6
- for H < 2500 m, α = 0.6..0.8.

The condition is that Sn is less than 33.

$$Sn = \frac{Q_l}{1440 \cdot A_{pist} \cdot \alpha} \tag{3}$$

Where:

- A_{pist} – pump piston area,
- Q_l– the liquid flow rate of the well.

Knowing the frequency value determines the surface stroke:

$$S_c = \frac{S_n}{n} \tag{4}$$

Depending on S_c, the standardized stroke S, immediately superior to the value of S_c, is chosen from the pump unit sheet.

III. DIMENSIONING THE EXTRACTION THRESHOLD

Among all the components of the pumping equipment, the rods stand out as the most crucial.

Their demand is unparalleled, making them the key factor that determines the pumping depth.

Quantifying the efforts in the pumping rods is a complex task that requires careful analysis.

The challenging working conditions further complicate the qualitative calculation of these efforts.

The diameter of the rods is determined by the depth of the well and the diameter of the extraction pipes in which they work. The depth and the way of preparing the seal can be:

- gasket with uniform section
- combined gasket.

The environment where the sticks will be worked determines the material from which they are made.

When calculating the pump rod gasket, the following are taken into account:

- the weight of the rods must be minimal for the permissible load for the polished rod;
- the elongation of the gasket must be minimal to have as little stroke loss as possible;
- the section of the rods and their material must be chosen in such a way as to withstand the stresses produced during operation, even to possible changes in the working conditions (flooding, increase in flow rate, etc.).

Several methods are used to size pump rod liners. Currently, the calculation of the rods is done statically or based on the fatigue resistance of the oil.

The choice of the diameter and the length of the sections is made by the static method in two hypotheses:

- minimum weight gaskets
- gaskets of equal resistance.

Determining the length of the sections consists of determining the point (starting from the bottom up) where the maximum unit stress in the beam is equal to the allowable unit stress.

Above this point, take a stick of standardized diameter, immediately higher, determining another point under the same conditions.

Repeat until $\sum l_{pi} \geq L$.

Where $\sum l_{pi} > L$, then the length of the sections is corrected until $\sum l_{pi} = L$.

This dimensioning method saves material and reduces the load in the polished rod, but due to the elastic deformations of the gasket, the actual stroke of the pump piston is reduced.

$$p_l = L \cdot \rho_{am} \cdot F_p \tag{5}$$

$$b = 1 - \frac{\rho_{am}}{\rho_o} \tag{6}$$

$$m_{asc} = \frac{S \cdot n^2}{1790} \left(1 + \frac{r}{l}\right) \tag{7}$$

$$l_{p1} = \frac{\sigma_{ad} \cdot (f_{p1} - p_1)}{q_{p1}(b + m_{asc})} \tag{8}$$

$$l_2 = \frac{\sigma_{ad} \cdot (f_{p2} - f_{p1})}{q_{p2}(b + m_{asc})} \tag{9}$$

$$l_{p3} = \frac{\sigma_{ad} \cdot (f_{p3} - f_{p2})}{q_{p3}(b + m_{asc})} \tag{10}$$

Where $\sum l_{pi} > L$, then the sections are corrected:

$$l_{p1}^{'} = \left(1 - \frac{\Delta L}{L}\right) \cdot l_{p1} \tag{11}$$

$$l_{p2}^{'} = \left(1 - \frac{\Delta L}{L}\right) \cdot l_{p2} \tag{12}$$

$$l_{p3}^{'} = \left(1 - \frac{\Delta L}{L}\right) \cdot l_{p3} \tag{13}$$

where: $\Delta L = \sum l_{pi} - L$

The maximum and minimum unit stresses in the bundle of rods is:

$$\sigma_{min_1} = \frac{p_l}{f_{p1}} \tag{14}$$

$$\sigma_{max_1} = \frac{p_l + l_{p1} \cdot q_{p1} \cdot (b + m_{asc})}{f_{p1}} \tag{15}$$

$$\sigma_{min_2} = \frac{p_l + l_{p2} \cdot q_{p2} \cdot (b + m_{asc})}{f_{p2}} \tag{16}$$

$$\sigma_{max_2} = \frac{p_l + (\sum_1^2 l_{pi} \cdot q_{pi}) \cdot (b + m_{asc})}{f_2} \tag{17}$$

$$\sigma_{min_3} = \frac{p_l + (\sum_1^3 l_{pi} \cdot q_{pi}) \cdot (b + m_{asc})}{f_3} \tag{18}$$

$$\sigma_{max_3} = \frac{p_l + (\sum_1^3 l_{pi} \cdot q_{pi}) \cdot (b + m_{asc})}{f_3} \tag{19}$$

Where $\sum l_{pi} > L$, then in the given formulas, $l_{pi} = l_{pi}^{'}$, σ_{ad} is the admissible unit effort of the material from which they are made the pumping rods.

In choosing the extraction pipes outside of the resistance calculation, taking into account, dimensioning from the surface to the bottom of the probe, the depth of paraffin deposition (from this depth to the surface a constant diameter is maintained) and the possibility of clamping the pumping rods, in the event that they broke at the well.

Thus, in order to allow the mechanical dewaxing of the extraction pipes, a constant diameter is required at a depth of about 1000 m, in order to have a constant diameter in order to allow the dewaxing operation to be carried out.

It is checked if the diameter change at the rods is done at the same point as the diameter change at the pipes.

If this is found, the length of the pipe section is increased by at least 10 m.

Maximum and minimum unit stresses in pipes is calculated to the relations:

$$p_p = \sum_{i=1}^{3} l_{pi}\, q_{pi} \tag{20}$$

$$p_p = \sum_{i=1}^{3} l_{pi}^{'}\, q_{pi} \tag{21}$$

$$F_{ti} = \frac{\pi}{4} d_{ti}^2 \tag{22}$$

$$p_l = (F_{t1} - f_{p1})\rho_{am} \cdot l_{am} + (F_{t1} - f_{p2})\rho_{am} \cdot l_{p2} + (F_{t1} - f_{p3})\rho_{am} \cdot l_{p3} \tag{23}$$

$$p_l^{'} = (F_{t1} - f_{p1})\rho_{am} \cdot l_{am}^{'} + (F_{t1} - f_{p2})\rho_{am} \cdot l_{p2}^{'} + (F_{t1} - f_{p3})\rho_{am} \cdot l_{p3}^{'} \tag{24}$$

$$p_l^{''} = (F_{t2} - F_{t1})\rho_{am} \cdot l_{t2} \tag{25}$$

$$\sigma_{min\,1} = \frac{p_l^{'} + p_p}{f_{t1}} \tag{26}$$

$$\sigma_{max\,1} = \frac{p_l^{'} + p_p + l_{t1} q_{t1}}{f_{t1}} \tag{27}$$

$$\sigma_{min\,2} = \frac{p_l^{'} + p_l^{''} + p_p + l_{t1} q_{t1}}{f_{t2}} \tag{28}$$

$$\sigma_{max\,2} = \frac{p_l^{'} + p_l^{''} + p_p + \sum_{i=1}^{2} l_{ti} q_{ti}}{f_{t2}} \tag{29}$$

Analytical calculation of the actual stroke of the piston is determined by relations:

$$S'_r = S \cdot \left[1 + \frac{\omega^2}{2gE} (\sum l_{pi} \cdot q_{pi})(\sum \frac{l_{pi}}{q_{pi}})\right] - \lambda \tag{30}$$

$$\lambda = \frac{p_l}{E}\left(\sum \frac{l_{pi}}{a_{pi}} + \sum \frac{l_{ti}}{a_{ti}}\right) \tag{31}$$

for combined gasket:

$$S_r = S \cdot \left[1 + \frac{2{,}65}{10^{10}}(L \cdot n)\right] - \lambda \tag{32}$$

for single gasket:

$$S_r = \left[1 + \frac{2{,}25}{10^{10}}(L \cdot n)\right] - \lambda \tag{33}$$

$$p_l = \rho_{am} \cdot g \cdot F_p \cdot L \tag{34}$$

$$\rho_{am} = (1 + i)\rho_{am} + i \cdot \rho_a \tag{35}$$

where:
- S - polished rod stroke,
- S_r - actual piston stroke,
- λ - total elastic elongation,
- n - the number of double strokes/minute of the polished rod,
- E - longitudinal modulus of elasticity,
- p_l - the load created by the liquid column on the liquid,
- l_{pi} - the length of the rod sections,
- f_{pi} - section of the rods,
- q_{pi} - the unit weight of the rods,
- l_{ti} - the length of the extraction pipes,
- f_{ti} - section of extraction pipes,
- F_p - piston section,
- L - the length of the pump rod assembly,
- ρ_{am} - the density of the extracted liquid,
- ρ_t - the density of the extracted crude oil,
- ρ_a - the density of the reservoir water,
- i - the percentage of impurities,
- g - gravitational acceleration,

The volumetric or filling efficiency, plays an important role in assessing the correct or faulty operation of the submersible pump is given by the relationship.

$$\eta_v = \frac{Q_{ext}}{Q_{teor}} \cdot 100 \tag{36}$$

where:

$$Q_{teor} = 1440 \cdot F_p \cdot \min(S_r, S'_r) \cdot n \cdot \eta_u \cdot \eta_s \tag{37}$$

$$Q_{teor} = 1440 \cdot F_p \cdot max(S_r, S_{r'}) \cdot n \cdot \eta_s \cdot \eta_u \tag{38}$$

$$\eta_u = 1;$$
$$\eta_s = 0{,}9.$$

Where:
- Q_{ext} - the extracted liquid flow rate,
- Q_{teor} - theoretical flow rate,
- η_v - volume yield,
- η_s - loss yield,

-η_c - stroke efficiency.

During a pumping cycle, the self-weight of the pump packing affected by the buoyancy factor acts on the polished rod, the weight of the liquid column that is lifted by the pump piston, the frictional forces from the friction of the rods in the extraction pipes, the friction of the piston in the pump cylinder and the hydraulic resistance due to the movement of the liquid in the extraction pipes.

These forces, constant in both strokes, are static forces (loads).

During the same pumping cycle, the moving mass, represented by the pump rod set and the liquid in it, move with different accelerations, resulting in inertial forces called dynamic loads.

In the calculation of the loads from the polished rod, for the probes analyzed, we took into account both the dynamic and the static loads.

This calculation system offers greater precision, the values calculated in this system approaching those obtained with the help of dynamographs.

$$pl_{asc_{max}} \tag{39}$$

$$pp_{desc_{min}} \tag{40}$$

$$b = 1 - \frac{\rho_{am}}{\rho_0} \tag{41}$$

$$m_{asc} = \frac{S \cdot n^2}{1790}(1 + \frac{r}{l}) \tag{42}$$

$$m_{desc} = \frac{S \cdot n^2}{1790}(1 - \frac{r}{l}) \tag{43}$$

$$p_p = \sum l_{pi} \cdot q_{pi} \tag{44}$$

$$\rho_{am} = (1 - \frac{i}{100})\rho_t + \frac{i}{100} \cdot \rho_a$$

(45)

where:

- p_{max} - the maximum load from the polished rod,
- p_{min} - the minimum load from the polished rod,
- b - buoyancy factor,
- ρ_o - steel density,
- m_{asc} - dynamic factor in the upward force,
- m_{desc} - dynamic factor for downward force,
- r - the length of the crank of the pumping unit,
- l - the length of the connecting rod of the pumping unit,
- p_p - the weight of the pump rod assembly,
- r - the length of the crank of the pumping unit,
- l - the length of the connecting rod of the pumping unit,
- p_p - the weight of the pump rod assembly.

In order to calculate the maximum torque at the reducer, different calculation relations have been proposed.

We used the formula recommended by the A.P.I.

Given the errors that are committed with this approximate method, it is recommended that, for the reducer chosen, the maximum torque be higher than the previously calculated one by (15...20)%.

$$C\frac{S}{2}max_{max} \tag{46}$$

$$C_{min\,a} = (1{,}15\ldots1{,}25) \cdot C_{max} \tag{47}$$

where:

- C_{max} - the maximum torque at the reducer,
- P_{max} - maximum load on the polished rod,
- S - polished rod stroke,
- $C_{min\,a}$ - the minimum torque of the selected reducer.

The rated power of the electric motor is given by the relationship:

$$N_n = 0{,}1205 \cdot Q_t \cdot 10^{-3} \cdot L_f^{1{,}13} \tag{48}$$

To balance the pumping unit, calculate the total weight of the counterweights, G_m:

$$G_m = 4 \cdot G_{1g} \cdot 9{,}81 \tag{49}$$

Then the distance from the center of rotation to the center of deadweight is determined R_1:

$$R_1 = \frac{G \cdot r}{G_m} \tag{50}$$

unde:

- G_m – the total weight of the counterweights,
- r – crank length.

IV. CONCLUSIONS

As technology advances, integrating numerical modeling and computer simulations is expected to play an increasingly important role in the petroleum industry.

The future promises innovations that will transform how pumping wells are designed and operated, bringing substantial economic and environmental benefits.

Also, collaboration between researchers, engineers and technology companies will be essential to develop sustainable and effective solutions.

This collaborative effort will make everyone involved feel included and part of the solution. Investments in research and development will drive the discovery of new technologies and methods that will continue to improve operational performance and protect the environment.

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