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Research Article

Research of Optimization Method of Swabbing Parameters of All Rods Pumping Wells in the Entire Oilfield

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Abstract: Aiming at the drawbacks of the optimization and design methods and the practical production goal of least energy consumption, a new theory is raised that the gas of the layer released energy in the lifting process including two parts: dissolved-gas expansion energy and free-gas expansion energy. The motor's input power of rod pumping system is divided into hydraulic horse power, gas expansion power, surface mechanical loss power, subsurface loss power. Using the theory of energy-conservation, the simulation model of free-gas expansion power has been established, the simulating models of the motor's input power which are based on the energy method have been improved and the simulation precision of system efficiency has been enhanced. The entire optimization design models have been set up in which the single-well output is taken as the optimum design variable, the planed production of all oil wells in an overall oilfield as the restraint condition and the least input power of the overall oilfield as the object. Synthesizing the optimization design results of the single well and the entire oilfield, the optimal output and the optimal swabbing parameters of all wells can be got. The actual optimizing examples show that the total power consumption designed by the entire optimization method is less 12.95% than that by the single optimization method.

Keywords: Entire oilfield, gas expansion energy, least energy consumption, optimization, Pumping oil wellsystem efficiency

INTRODUCTION

The sucker rod pumping system is the most popular artificial lift system all over the word (Brown, 1982). The sucker rod pumping system consists mainly of five parts including (Nind, 1981; Brow, 1982; Hirschfeldt *et al*., 2007; Ghareeb *et al*., 2007):

- The subsurface sucker rod-driven pump
- The sucker rod string
- The surface pumping equipment
- The power transmission unit
- The prime mover

It is suggested from studies that optimizing the swabbing parameters is an effective way to enhance the system efficiency of pumping well (Gault, 1987; Lekia and Evans, 1995; Shedid, 2009). Domestic and foreign scholars have made great contribution in designing and optimizing method of the parameters of pumping wells (Han *et al*., 1995; Mo, 2000; Yao, 2005). Gibbs (1982) and Xu(2000) proposed the method which was based on a given output constraints or not consider production for restraint and chose the maximum system efficiency as the objective function; the method introduced by Zhen and Deng (2007) was based on a given output as constraint and chose the least energy consumption as the objective function. In essence, the objective functions above were consistent, because the maximum system efficiency could be achieved when the energy consumption is least for the constant production. The above results indicated that most optimization and design of swabbing parameters of pumping wells centered on the single well.

And these previous models all considered that the free-gas had been blown out from the casing or the free-gas only influences the pump efficiency and ignored the energy of free-gas releasing itself. Zhen and Deng (2007) calculated dissolved-gas expansion power, but still ignored the free-gas expansion power.

The ultimate objective of pumping well is to produce crude oil. Current circumstance in China is that the oil production is planned by the oilfield. As a result, the least energy consumption in the whole oilfield could not be guaranteed to achieve, even when the system efficiency of single well is top for the existence of difference in liquid supply and water cut of different wells. Aiming at the practical production situation and the drawbacks of the optimization and design methods, an improved calculation method of system efficiency of

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rod pumping wells considering influence of free-gas was set up basing on the energy consumption method and the simulation and optimization method of swabbing parameters of rod pumping wells was proposed in this study, with the least energy consumption as the objective function. Namely, taking all the wells into account, all the swabbing parameters of pumping wells and the corresponding fluid production rates and flowing pressures at the premise of the completion of planed oil production were optimized.

SYSTEM EFFICIENCY SIMULATIONMODEL

Hydraulic power simulation model: At present, the methods for calculating the hydraulic power spent on fluid lifting is expressed as follows:

$$N_e = \frac{Q\rho_l Hg}{86400} \times 10^{-3} \tag{1}$$

where,
N_e = The effective power, kW
Q = The actual fluid rate of well, m^3/d
ρ_l = The liquid density kg/m^3
H = The effective lifting height, m
g = The acceleration of gravity, m/s^2
in which:

$$H = H_d + \frac{p_o - p_c}{\rho_l g} \tag{2}$$

$$\rho_l = f_w \rho_w + (1 - f_w)\rho_o \tag{3}$$

where,
H_d = The working fluid level, m
p_o = The surface tubing pressure, Pa
p_c = The casing pressure, Pa
f_w = The water-cut, %
ρ_w = The water density, kg/m^3
ρ_o = The crude oil density, kg/m^3

Input power simulation model: The input power in this study consists of three parts: hydraulic power, power loss and gas expansion power. The power loss includes the surface mechanical power loss and down-hole power loss. The down-hole power loss is constituted by the stuffing box power loss, viscous friction power loss, sliding friction power loss and pump power loss.

- **Gas expansion power simulation model:** The energy generated by the gas in the lifting process contains the solution gas expansion energy and free-gas expansion energy.

  - **Free-gas expansion power:** The free-gas expansion power is defined as the power used to lift the liquid, which is generated by the gas expansion.

Assumed the volume of free-gas is V_s as the suction pressure is p_s and the volume is V_w for the tubing head pressure p_w. The volume of free-gas is V_x for any in an arbitrary pressure p.
Presumed the gas expands isothermally, then:

$$p_s V_s = p V_x \tag{4}$$

$$p_s V_s = p_w V_w \tag{5}$$

in which:

$$V_w = (R_p - \alpha p_s)Q_o \tag{6}$$

where,
V_s = The volume of free-gas under the suction pressure, m^3
V_w = The volume of free-gas at wellhead, m^3
V_x = The volume of free-gas under any arbitrary pressure, m^3
p = The arbitrary pressure in the expansion (absolute), MPa
p_w = The tubing head pressure (absolute), MPa

Then the work did by the free-gas in expansion can be got as follows:

$$\begin{aligned} A &= -\int_{p_s}^{p_w} (V_x - V_s)\mathrm{d}p \\ &= 10^3 (R_p - \alpha p_s) Q_o p_w \left(\ln \frac{p_s}{p_w} + \frac{p_s - p_w}{p_s}\right) \end{aligned} \tag{7}$$

where,
A = The work did by free-gas, kJ

Then the free-gas expansion power could be calculated as follows:

$$P_z = \frac{10^3 (R_p - \alpha p_s) Q_o p_w}{86400} \left[\ln \frac{p_s}{p_w} + \frac{p_w - p_s}{p_s} \right] \tag{8}$$

where,
P_z = The free-gas expansion power, kW

  - **Solution-gas expansion power:** The Solution-gas expansion power is defined as the power transformed from the gas volume expansion for lifting liquid. The solution gas expansion power calculation model could be developed with the conversation law:

$$P_e = \begin{cases} \dfrac{10^3 \alpha Q_o p_b p_w}{86400} \ln \dfrac{p_b}{p_w} (p_s \geq p_b, p_w < p_b) \\ 0 \qquad (p_s \geq p_b, p_w \geq p_b) \\ \dfrac{10^3 \alpha Q_o p_s p_w}{86400} \ln \dfrac{p_s}{p_w} (p_s < p_b, p_s > p_w) \\ 0 \qquad (p_w > p_s, p_s < p_b) \end{cases} \tag{9}$$

where,
P_e = The solution-gas expansion power, kW
Q_o = The oil production, m^3/d
p_b = The saturation pressure(absolute), MPa

  - **Gas expansion power:** The gas expansion power is the sum of the solution gas expansion power and free-gas expansion power:

$$P_g = P_e + P_z \tag{10}$$

where,
P_g = The gas expansion power, kW.

- **Surface mechanical power loss simulation model:** The surface mechanical power loss simulation model in Zhen and Deng (2007) is expressed as follows:

$$P_u = P_d + (F_u - F_d)Snk_1 + (F_u + F_d)Snk_2 \tag{11}$$

where,
P_u = The surface mechanical power loss, kW
F_u , F_d = The average rod load in up-stroke and down-stroke, kN
k_1, k_2 = The transmissibility coefficient

- **Down-hole power loss calculation model:** The down-hole power loss can be calculated as follows (Feng *et al*., 2005; Gabor, 2010):

$$P_d = \Delta P_P + \Delta P_N + \Delta P_M + \Delta P_{Pu} \tag{12}$$

where,
ΔP_d = The down-hole power loss, kW
ΔP_P = The stuffing box power loss, kW
ΔP_N = The viscous friction power loss, kW
ΔP_M = The sliding friction power loss, kW
ΔP_{Pu} = The pump power loss, kW

- **Input power simulation model:** The system input power is the sum of all the powers:

$$P_i = N_e + P_u + P_d - P_g \tag{13}$$

where,
P_i = The input power, kW

The system efficiency can be calculated as follows:

$$\eta_i = \frac{N_e}{P_i} \times 100\% \tag{14}$$

where,
η_i = The system efficiency

LEAST ENERGY CONSUMPTION SIMULATION AND REGRESSION MODEL

For any given oil production rate Q in a single well, taking the system input power as the objective function and optimizing the swabbing parameters and rod string, then the least system input power of different production rate and the corresponding optimal swabbing parameters can be determined.

Least energy consumption simulation optimization model:

- **Design variables:** Take the stroke S, the pumping speed n, the pump size D, the pump setting depth L, the rod string(the diameter of k grade rod is d_k and the length is L_k, k=1, 2, …, m):

$$\{X\} = \{S, n, D, L, (d_k, L_k : k = 1, 2, \cdots, m)\} \tag{15}$$

- **Objective function:** When the device type, well parameters, management parameters and casing parameters were fixed, the system efficiency is just the function of swabbing parameters (Mccoy *et al*., 2001). Taking the least input power as the object, the optimization design objective function can be written as follows:

$$MinF\left(S, n, D, L, (d_k, L_k : k = 1, 2, \cdots, m)\right) \tag{16}$$

- **Constraint condition:** When optimize the swabbing parameters of single well, it is needed to fix the production rate, the utilization efficiency of maximum rod load, the utilization efficiency of motor and the intensity of rod string.
- **Simulation and optimization model of a single well:** The simulation and optimization model of a

single well is made up of the objective function and constraint condition. With the optimization algorithm, the least input power and the corresponding swabbing parameters of a single well at different production rate can be calculated.

Regression model: Basing on the simulation and optimization result of the least system input power of different production rate Q, the regression model of the least energy consumption and the production could be developed as follows:

$$P_j = a_{0j} + a_{1j}(Q_j - Z_j) + a_{2j}(Q_j - Z_j)^2 + a_{3j}(Q_j - Z_j)^3 \quad (17)$$

where,

P_j = The least input power of well j for Q_j, kW

$a_{0j}, a_{1j}, a_{2j}, a_{3j}, Z_j$ = The regression coefficients of well j

SYSTEM OPTIMIZATION MODEL

As the prerequisite of oil production rate in the whole oilfield is achieved, taking the least energy consumption of the whole oilfield as the object, the liquid production rate and the corresponding swabbing parameters of every well are optimized.

Design variables: Define the fluid production rates of wells as the design variables:

$$X = \{Q_j, j = 1, 2, \cdots, N\} \quad (18)$$

where,

N = The number of wells in the oilfield

Objective functions: Take the least system input power as the objective function of swabbing parameters optimization:

$$MinF(X) = Min\sum_{j=1}^{N}\{a_{0j} + a_{1j}(Q_j - Z_j) + a_{2j}(Q_j - Z_j)^2 + a_{3j}(Q_j - Z_j)^3\} \quad (9)$$

Constraint conditions: The oil production rate of the oilfield should be equal to the planed oil production rate:

$$H(1) = \sum_{j=1}^{N} Q_j \times (1 - n_{wj}) - Q_o = 0 \quad (20)$$

where,

n_{wj} = The water cut of the well j

Q_o = The planed oil production rate of the oilfield, t/d

Optimization mathematical model: According to the objective function and constraint conditions above, the fluid production rate and swabbing parameters optimization model is established as follows:

$$\begin{cases} Min\sum_{j=1}^{N}\{a_{0j} + a_{1j}(Q_j - Z_j) + a_{2j}(Q_j - Z_j)^2 + a_{3j}(Q_j - Z_j)^3\} \\ H(1) = \sum_{j=1}^{N} Q_j \times (1 - n_{wj}) - Q_o = 0 \end{cases} \quad (21)$$

The extreme question above could be solved with the optimization algorithm of penalty function and then the optimal fluid production rate could be determined.

APPLICATION

The swabbing parameters of ten pumping wells in Jilin Oilfield were optimized with the models since September 2009. The current producing parameters, input power and system efficiency of the ten wells were listed in Table 1.

Least energy consumption of different production rate in a single well: The least system input power and swabbing parameters of different production are optimized for a single well. As shown in Fig. 1, the relationship between the least energy consumption and the liquid production rate could be observed.

Optimized results of the least energy consumption for a single well: As the liquid production rate of each well is constant, then optimize the swabbing parameters of each well in Table 1 and the results are listed in Table 2.

Optimized results of the least energy consumption for the entire oilfield: As the total oil rate of ten wells

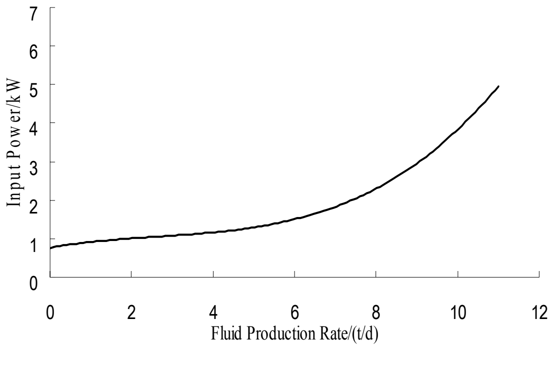

Fig.1: Relation of the least energy consumption with liquid production rate

Table 1: The swabbing parameters of ten wells in an oilfield before optimization

Well	Stroke length /m	Frequency of stroke.min	Pump diameter /mm	Pump setting depth/m	Dynamic liquid level/m	Water cut/%	Liquid production rate/(t/d)	Oil production rate/(t/d)	Input power/kW	System efficiency/ %
1	2.53	5.17	38	1205	1109	7.1	9.60	8.92	4.01	30.23
2	2.46	4.53	38	1375	1015	80.0	13.90	2.78	6.49	27.09
3	2.38	5.95	38	1226	1158	6.4	10.42	9.75	5.55	26.19
4	2.55	4.45	44	1280	1150	60.0	11.20	4.48	4.21	28.23
5	2.52	4.48	44	1273	1190	6.8	6.58	6.13	4.20	27.69
6	2.48	4.85	38	1305	1102	7.2	9.56	8.87	4.32	29.12
7	2.46	4.17	38	1296	922	50.0	10.36	5.18	4.79	27.44
8	2.43	5.02	44	1312	1069	45.6	10.32	5.61	4.68	29.06
9	2.50	3.32	38	1356	636	6.4	10.88	10.18	3.22	28.76
10	2.50	5.31	32	1361	689	75.0	13.85	3.46	4.39	30.86
Total (Average)							106.67	65.36	45.86	(28.47)

Table 2: The optimized swabbing parameters of the ten wells by the single well optimizing method

Well	Stroke length/ m	Frequency of stroke.min	Pump diameter /mm	Pump setting depth/m	Dynamic liquid level/m	Water cut/%	Liquid production rate/(t/d)	Oil production rate/(t/d)	Input power /kW	System efficiency /%
1	2.5	5.65	32	900	764	7.1	9.60	8.92	2.76	35.40
2	3.0	4.28	32	1000	699	80.0	13.90	2.78	3.69	34.55
3	2.5	3.00	44	1378	1227	6.4	10.42	9.75	4.24	35.20
4	2.5	3.86	38	1100	720	60.0	11.20	4.48	3.71	33.62
5	2.5	3.60	32	1026	845	6.8	6.58	6.13	2.31	34.53
6	3.0	3.16	44	960	732	7.2	9.56	8.87	3.42	33.75
7	2.5	2.89	38	900	586	50.0	10.36	5.18	2.95	32.28
8	2.5	3.68	38	1050	862	45.6	10.32	5.61	3.64	34.26
9	1.8	3.79	56	1200	710	6.4	10.88	10.18	2.95	35.53
10	2.5	3.00	44	1060	708	75.0	13.85	3.46	3.62	35.58
Total (Average)							106.67	65.36	33.29	(34.47)

Table 3: The optimized swabbing parameters of the ten wells by the entire optimization method

Well	Stroke length /m	Frequency of stroke /min^{-1}	Pump diameter /mm	Pump setting depth/m	Dynamic liquid level/m	Water cut/%	Liquid production rate/ (t/d)	Oil production rate/(t/d)	Input power /kW	System efficiency /%
1	2.5	4.42	32	900	696	7.1	9.42	8.75	2.45	34.68
2	2.0	3.75	32	1378	230	80.0	8.10	1.62	2.23	23.32
3	3.0	4.44	44	1000	799	6.4	10.38	9.72	3.09	36.68
4	1.8	4.25	32	1280	465	60.0	6.13	2.45	2.08	18.63
5	2.5	3.96	38	900	671	6.8	8.72	8.13	2.53	24.12
6	3.0	4.16	44	1305	894	7.2	12.86	11.93	3.95	37.45
7	2.5	2.65	38	900	498	50.0	9.65	4.83	2.63	30.12
8	2.0	3.88	38	1312	523	45.6	6.80	3.70	2.16	29.36
9	1.8	3.49	56	1102	989	6.4	13.33	12.48	4.02	39.46
10	1.8	4.60	44	1429	73	75.0	7.00	1.75	2.21	27.02
Total (Average)							92.39	65.36	27.35	(30.08)

is constant, then optimize the swabbing parameters of whole area and the results were listed in Table 3.

Comparison and analysis on the optimization results: As ten wells were optimized separately, the average system efficiency was increased from 28.47 to 34.47 with 6%, respectively enhanced; the system input power of the oilfield is decreased from 45.86 to 33.29kW, respectively with energy saving of 27.41%. After the integral optimization of the ten wells, average system efficiency was increased to 30.08 with 1.61%, respectively enhanced and the enhancement effect is worse than the optimized results of single well. However, the system input power is reduced from 45.86 to 27.35kW, respectively with energy saved 40.36%. Compared with the optimized results of single well, the energy consumption is saved 12.95% further.

Obviously, it is found that the average system efficiency optimized entirely is lower than the optimized results of single well, but the total energy consumption is further reduced and the power saving is obvious. This is because the constraint conditions of the two optimization methods are different. Both the total production rate and each well production rate are constrained to be constant in the optimization of single well. However, the corresponding flowing pressure is not always the optimum one. For the integral optimization, the total oil production rate is only constrained and both the swabbing parameters and the oil production rate of every well are optimized. That is to say that the flowing pressure of each well is also optimized. After applying the integral optimization, the total liquid production rate of the oilfield is reduced and that is the fundamental reason causing further energy saving.

CONCLUSION

- The free-gas expansion power calculation model is established with considering the energy generated by the gas expansion. Therefore, gas expansion power is composed of solution gas expansion power and free-gas expansion power. Taking the gas energy into account, the input power simulation model is improved and the system efficiency simulation accuracy is raised.
- Taking the single well as the optimization object, the least energy consumption of different liquid production rate is optimized and the regression equation of the least energy consumption versus the liquid is formulated. It is verified that the least system input power increased cubically with the liquid production rate. Consequently, the system efficiency can be improved obviously after optimization, when system input power increases significantly.
- Compared with the optimization results of single well, the total energy consumption after integral optimization could be further reduced. The reason is that the integral optimization and design model assumes that the total oil production rate of the oilfield is unchanged, the total fluid production rate is decreased after the optimization and the system input power is reduced significantly. Especially for an oilfield, if there are big difference in water cut and fluid production rate of different well patterns or wells, the energy saving effect would be more significant.

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