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Study on Sensitivity of Plunger Characteristic Parameters to Gas Well Production

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Abstract: Plunger dewatering gas extraction is a technology primarily used for low-yield natural gas collection. To maximize the efficiency of plunger dewatering gas extraction, optimization design is necessary. This study is based on the principles of plunger lifting dewatering gas extraction. By calculating the distribution of fluid and pressure in the wellbore during the plunger's upward movement at startup, as it reaches the wellhead, and during well shut-in, the interconversion relationship between plunger upward liquid discharge, self-jet flow, and well shut-in pressure recovery processes is analyzed. An optimization algorithm for plunger design is developed. When calculating the impact of plunger characteristic parameters on gas well production, the study considers the effect of gas compressibility factor varying with temperature and pressure, which makes the research results more realistic. The findings of this study contribute to optimizing the process parameters of plunger dewatering gas extraction and enhancing gas well production.

1. Introduction

In today's oil and gas industry, plunger lift gas drainage is a traditional technique for enhancing oil well production, characterized by its simple equipment, easy maintenance, and operational convenience. With the increasing scarcity of oil and gas resources, optimizing the plunger lift gas cycle to achieve maximum oil well production has become a hot research topic. Therefore, the study of optimization design methods for plunger lift gas drainage holds significant practical significance.

Previous studies have focused on optimizing the plunger lift gas cycle by varying parameters such as plunger diameter, gas-liquid ratio, and plunger descent velocity. For example, Su[1] et al. (2018) successfully increased oil well production by optimizing plunger diameter and gas-liquid ratio. However, these parameters are influenced by wellbore conditions, necessitating the consideration of wellbore conditions on plunger lift gas drainage. With advancements in technology, research on optimizing the plunger lift gas cycle through computer simulations and optimization algorithms has increased. For instance, Xie[2] et al. (2020) employed a genetic algorithm to determine the optimal gas-liquid ratio and plunger descent velocity by simulating changes in fluid level during plunger movement. Li[3] et al. (2021) utilized a particle swarm optimization algorithm and multiple evaluation criteria to establish a mathematical model for optimizing the plunger lift gas cycle.

Moreover, in recent years, there has been a focus on optimization design methods for plunger lift gas drainage based on wellbore condition transition criteria. For instance, Zhang[4] et al. (2019) proposed an optimization design method based on wellbore condition transition criteria through experimental studies and numerical simulations. This method divided the wellbore conditions into drainage and gas production segments and addressed the optimization design issues for each segment, successfully enhancing oil well production.

Against this backdrop, this study is based on the principles of plunger lift gas drainage, specifically the plunger ascending liquid discharge, self-priming flow, and well shut-in repressurization processes. By analyzing the interconversion relationships between these processes and considering the distribution of fluid and pressure in the wellbore during the plunger startup, ascent to the wellhead, and well shut-in, a plunger lift gas drainage optimization design method based on wellbore condition transition criteria is proposed. Sensitivity analysis of plunger characteristic parameters using this algorithm is conducted. Through in-depth research on plunger lift gas drainage, this study provides technical support and theoretical guidance for oil and gas exploitation, contributing to the realization of sustainable resource utilization.

2. Conversion of plunger drainage and gas production conditions

Plunger lift gas drainage is a periodic intermittent gas production method that typically involves three production stages. In the first stage, the plunger descends from the wellhead to the bottom of the well while the reservoir continues to produce gas, resulting in the accumulation of gas energy in the wellbore. In the second stage, the plunger is lifted to drain the wellbore. The annular space between the wellbore and the tubing stores high-pressure gas, which, upon pressure reduction, expands and propels the plunger with the entrained water towards the wellhead, effectively removing accumulated water from the wellbore. In the third stage, self-priming flow occurs as the plunger evacuates the accumulated liquid, allowing the natural gas and water from the reservoir to flow. As water accumulates in the wellbore, the production flow pressure gradually decreases, resulting in a decline in reservoir production. When the water accumulation reaches a certain level, the well is shut in and the cycle begins again.

The key to optimizing the design of plunger lift gas drainage lies in capturing three critical time points: the plunger startup, the plunger reaching the wellhead, and the well shut-in. By calculating and analyzing the distribution of fluid and pressure in the wellbore at these time points, it becomes possible to accurately analyze the plunger ascent process, self-priming flow process, and well shut-in repressurization process. This analysis allows for an understanding of the coordination between gas supply and discharge during these processes and provides insights into the energy conversion mechanisms within the wellbore.

2.1 Distribution of ponded water in the wellbore when the plunger starts up

As shown in Figure 1, when the plunger is started up, the water in the wellbore is mainly the water in the tubing, the water in the casing annulus, and the water in the casing annulus on the tubing foot.

It can be seen from the figure that when the plunger is started upward, the oil pressure casing pressure corresponding to the wellbore is the maximum casing pressure P_{cmax} and the maximum oil pressure P_{tmax}, and the bottom hole pressure at this time is the maximum flow pressure P_{wfmax}. In the figure 1, $H_{tJyUpStart}$ represents depth of accumulated water in the tubing, meters; $H_{cJyUpStart}$ represents depth of accumulated water in the oil jacket annulus, m; P_{ttmax} represents pressure at the tubing foot, MPa.

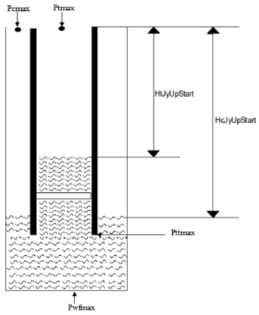

Figure 1: The distribution of wellbore accumulated water when the plunger starts up

2.2 Distribution of accumulated water in the wellbore when the plunger goes up to the wellhead

According to the formation productivity equation, the formation gas production and formation water production during the upward movement of the plunger can be calculated, and the opportunity distribution of the wellbore when the plunger is lifted to the wellhead can be calculated, as shown in Figure 2. At this time, using the natural gas state equation, the wellbore pressure distribution when the plunger is lifted to the wellhead can be calculated.

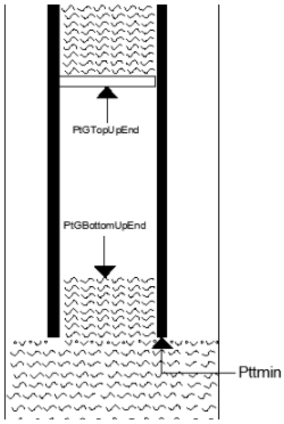

Figure 2: The distribution of wellbore accumulated water when the plunger is lifted to the wellhead

When the plunger is lifted to the wellhead, the water accumulated in the wellbore is mainly the water accumulated on the plunger and the water accumulated in the tubing. At this time, the pressure at the top of the tubing gas column is:

$$P_{tGTopUpEnd} = H_{tPyUpEnd} * R_{dwater} * 9.8 * 10^{-3} + P_{zx} + P_{fPy} + P_{tmin} \tag{1}$$

In the formula, $H_{tPyUpEnd}$: depth of liquid above the plunger, m; R_{dWater}: relative density of water produced in the formation, dimensionless; P_{fPy}: frictional resistance of the water column above the plunger, MPa; P_{zx}: additional power for lifting the plunger, MPa; P_{tmin}: wellhead Oil pressure; MPa.

According to the state equation of natural gas, the gas column bottom pressure $P_{tGTopUpEnd}$ can be calculated from the gas column top pressure $P_{tGBottomUpEnd}$ in the tubing.

At this time, according to the distribution of water in the wellbore when the plunger starts, the gas volume in the wellbore when the plunger rises to the wellhead, and according to the plunger lift principle, the oil ring air volume Vgc when the plunger starts can be calculated:

$$V_{gcUpStart} = V_{gcUpEnd} + V_{gtUpEnd} + V_{gLoss} - V_{gpUp} \tag{2}$$

In the formula, V gcUpEnd represents the gas volume in the pipe when the plunger rises to the wellhead, the standard party; V gtUpEnd represents the gas volume in the air of the casing at the wellhead; Vg loss represents the piston gas leakage during the wellhead, the standard party; V gpUp represents the formation gas production when the plunger rises to the wellhead, the standard party.

2.3 Distribution of wellbore accumulated water during plunger lift shut-in

When the plunger goes up to the wellhead, after the accumulated water above the plunger is emptied, the gas well enters the self-spraying continuous flow state. According to the continuous flow time of the gas well, the formation gas production V_{gpAf} and water production V_wpAf during the continuous flow period of the gas well can be calculated.

$$V_{gpAf} = C * \left(P_r^{\,2} - P_{wfAfavg}^{\,2}\right) * T_{Af}/1440 \tag{3}$$

$$V_{wpAf} = V_{gpAf}/R_{gw} \tag{4}$$

In the formula, C represents gas production index, standard square/MPa; P_r represents formation pressure, MPa; $P_{wfCloseavg}$ represents average flow pressure during well shut-in period, MPa; T_{af} represents preset self-flowing time, minutes; R_{gw} represents production Air-water ratio, standard square/square.

As the production time increases, the formation pressure is gradually insufficient, and the gas well cannot perform normal self-spraying. At this time, the gas well is closed and the plunger goes down to the bottom of the well. According to the formation gas production and water production during self-spraying continuous flow, the wellbore pressure distribution and water accumulation distribution when the gas well is shut in can be calculated, as shown in Figure 3.

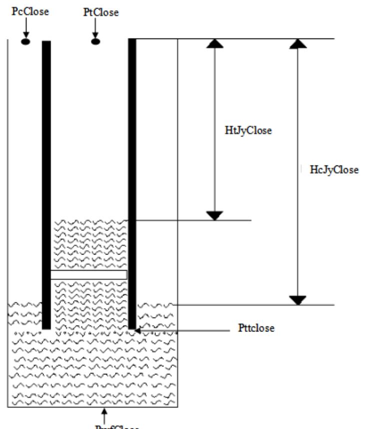

Figure 3: Water accumulation and pressure distribution in the wellbore when the gas well is shut in

It can be seen from the figure that when the gas well is shut in, there is already a certain amount of accumulated water in the tubing and the casing annulus. In the figure, $H_{tJyClose}$ represents depth of tubing water surface when shutting in the well, meters; $H_{cJyClose}$ represents depth of annular water surface when the well is shut in, meters; $H_{tJyClose}$ represents depth of tubing water surface when the well is shut in, meters; $H_{cJyClose}$ represents annular space volume when the well is shut in Depth of the water surface, m.

According to the wellbore pressure distribution and fluid distribution during the shut-in period, and the wellbore pressure distribution and fluid distribution when the plunger lift is started, the shut-in time, formation gas production rate and formation water production rate during the well shut-in period can be calculated.

Calculation of formation gas production $V_{gpClose}$ during well shut-in period:

$$V_{gpClose} = \left(V_{gcUpStart} + V_{gtUpstart}\right) - (V_{gcClose} + V_{gtClose}) \tag{5}$$

Calculation of formation water production $V_{wpClose}$ during well shut-in period:

$$V_{wpClose} = V_{gpClose}/R_{gw} \tag{6}$$

Well shut-in time T_{close} calculation:

$$T_{close} = 1440 * V_{gpClose}/C/({P_r}^2 - {P_{wfCloseavg}}^2) \tag{7}$$

Then, the exhaust output of the plunger is calculated according to the running time of the plunger, the continuous flow time of the flow jet, the shutdown time, the formation gas production when the plunger moves upward, the bottom gas production during the flow jet and the gas production of the gas reservoir during the shut-in period.

Daily gas production Q_{gpdCal} of plunger drainage gas production:

$$Q_{gpdCal} = (V_{gpUp} + V_{gpAf} + V_{gpClose})/(T_{up} + T_{af} + T_{close}) * 1440 \tag{8}$$

Daily water production Q_{wpdCal} of plunger drainage and gas recovery:

$$Q_{wpdCal} = Q_{gpdCal}/R_{gw} \tag{9}$$

In the above formula, $V_{gtUpStart}$ represents the gas volume in the tubing when the plunger starts upward, in standard square; $V_{gcUpstart}$ represents the gas volume in the casing annulus when the plunger starts upward, in standard square; $V_{gcClose}$ represents gas volume in the tubing when the well is closed, in standard squares; $P_{wfCloseavg}$ represents average production flow pressure when the well is closed, in MPa; VV_{gpUp} represents formation gas production during the upward movement of the plunger, in standard squares. V_{gpAf} represents Formation gas production during self-flowing of gas well, standard square; $V_{gpClose}$ represents Formation gas production during well shut-in, standard square; T_{up} represents Plunger up time, minutes; T_{af}: Gas well self-flowing time of continuous flow, minutes.

2.4 Feasibility judgment of plunger lift drainage for gas recovery

According to the technical principle of the plunger lift exhaust recovery technology, the wellbore gas comes from the formation gas production when the well is closed, and the bottom hole pressure when the plunger is started is the maximum production flow pressure Pwfmax. Therefore, it can be proposed that the plunger lift drainage. The conditions for judging the feasibility of gas production pressure are:

Maximum production flow pressure P_{wfmax} < formation pressure P_r.

The gas volume V_{gLift} lifted by the plunger for one drainage and gas recovery can be calculated based on the wellbore gas volume when the plunger starts up and the wellbore gas volume when the plunger goes up to the wellhead:

$$V_{gLift} = \left(V_{gcUpStart} + V_{gtUpStart}\right) - \left(V_{gcUpEnd} + V_{gtUpEnd}\right) \tag{10}$$

From this, it is also possible to calculate the gas-water ratio R_{gwLift} required to lift the plunger for drainage and gas recovery:

$$R_{gwLift} = V_{gLift}/V_{wpLift} \tag{11}$$

In the formula, V_{wpLift}: the amount of water produced by the plunger in the gas recovery formation once drained, square.

According to the gas-water ratio calculated above, combined with the principle of plunger drainage gas recovery technology, formation gas will also produce water at the same time. The gas feasibility pressure judgment condition is:

Plunger lift gas-water ratio R_{gwLift}< formation production gas-water ratio R_{gw}.

If gas wells are to be produced by plunger gas lift drainage, the bottomhole pressure and gas-water ratio must meet the above constraints.

3. Parameter setting and sensitivity analysis

The purpose of the plunger drainage optimization design algorithm is to adjust the basic parameters of the gas well plunger so that the daily gas production of the gas well can reach the set target gas production. Apply the plunger drainage gas recovery optimization algorithm to set the basic parameters of the formation, gas well and wellbore, and calculate the impact on the daily gas production of the gas well under different constraints based on the feasibility analysis of the plunger drainage gas recovery.

3.1 Basic parameter setting of plunger drainage and gas recovery

Due to the lack of real data, the project research provides a set of basic parameters based on the understanding of deep well plunger drainage gas recovery, based on which the adaptability of plunger drainage gas recovery is analyzed and studied.

(1) Setting of basic formation parameters.

The setting values of main formation parameters are shown in Table 1.

Table 1: Setting values of main formation parameters

Parameter name	Symbol	Unit of measure	Value
Formation medium depth	Hr	m	2000
Gas production index	C	M^3/MPa^2	30
Formation pressure	Pr	MPa	10
Production gas-water ratio	Rgw	standard square/square	2000
Wellhead temperature	Ttop	k	290
Well temperature gradient	Tgrad	k/m	0.015
Specific gravity of natural gas	RdGas	Dimensionless	0.76
Formation water specific gravity	RdWater	Dimensionless	1.003
Formation water viscosity	WaterVisc	centipoise	1.23

(2) Basic parameter setting of the wellbore.

The setting values of main wellbore parameters are shown in Table 2.

Table 2: Setting values of main wellbore parameters

Parameter name	Symbol	Unit of measure	Value
Casing inner diameter	Dci	m	0.121
Tubing outer diameter	Dto	m	0.073
Tubing inner diameter	Dti	m	0.062
Tube roughness	Eta	m	1.5*10-5
Oil pipe foot depth	Ht	m	3980
Case oil effusion height ratio	RjyCT	m/m	0.2

(3) Plunger characteristic parameter setting

The basic parameter values of the main plunger characteristics are shown in Table 3.

Table 3: Main plunger parameter settings

Parameter name	Symbol	Unit of measure	Value
Additional plunger resistance	Pplunger	MPa	0.35
Plunger up speed	vUp	m/min	240
Downward speed of plunger in air	vDownG	m/min	120
Downward velocity in plunger fluid	vDownW	m/min	60
Leakage speed of plunger	vWLoss	M^3/min	0.001
Plunger Air Leakage Velocity	vGLoss	M^3/min	0.5

3.2 Sensitivity Analysis of Plunger Drainage Depth to Gas Well Production

According to the above algorithm, the feasibility condition of plunger drainage and gas recovery must meet certain formation production gas-water ratio and formation pressure conditions. Under the basic conditions of given formation parameters and plunger parameters, the effects of different drainage depths on the gas production of gas wells are studied.

The calculation results are shown in Table 4. It can be seen from the table that as the drainage depth decreases, the production of the gas well decreases gradually, and the maximum production flow pressure of the gas well gradually increases.

Table 4: Effect of different wellbore depths on daily gas production of gas wells

Drain depth (m)	Production flow pressure (MPa)	lift air to water ratio (m3/m3)	Gas production (m3)
2000	5.450	557.245	3806.527
1980	5.764	569.326	3732.468
1960	6.061	581.450	3652.985
1940	6.359	593.641	3567.983
1920	6.659	605.893	3477.388
1900	6.960	618.198	3381.066
1880	7.263	630.553	3278.926
1860	7.567	642.952	3170.795
1840	7.873	655.392	3056.514
1820	8.181	667.873	2935.948

It can also be seen from the calculation results in the table that when the drainage depth is equal to the formation depth, the output is the maximum, but this situation does not occur in actual production, and the drainage depth of the gas well is higher than the wellbore depth of the gas well. satisfy:

$$\text{Wellbore depth } H_t\text{—drainage depth } H_z \geq R \tag{12}$$

R is the safety factor, which depends on the actual situation. It can be seen that the larger the drainage depth of the gas well is, the better the safety factor of the gas well is met.

3.3 Sensitivity Analysis of Plug Loss Rate to Gas Well Production

On the basis of the given parameters, the gas well production constraints are met, and the influence of different plunger leakage rates on the gas production of the gas well is studied and analyzed. Some calculation results are shown in Table 5.

Table 5: Effect of plunger loss rate on gas production of gas wells

Liquid loss rate(m3/min)	Maximum flow pressure(MPa)	lift air to water ratio(m3/m3)	Gas production(m3)
0.045	7.572	641.714	3167.984
0.05	7.781	650.149	3090.333
0.055	7.991	658.625	3009.715
0.09	9.483	719.025	2356.848
0.095	9.699	727.816	2249.582
0.1	9.917	736.646	2138.349
0.105	10.135	745.523	2022.779

It can be seen from the table that with the gradual increase of the plunger liquid loss rate, the maximum production flow pressure of the gas well and the production gas-water ratio are gradually increasing, and the production of the gas well also decreases accordingly. The specific analysis is shown in Figure 4.

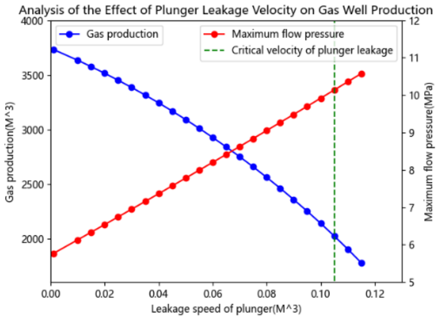

Figure 4: Sensitivity analysis of plunger leakage rate to gas well production

It can be seen from the figure that the leakage rate of the plunger is inversely proportional to the production of the gas well, that is, the smaller the leakage rate of the plunger, the higher the production of the gas well. In actual production, the leakage of the plunger should be reduced as much as possible. Similarly, when the leakage rate of the plunger reaches a certain value, the maximum flow pressure of the gas well will exceed the formation pressure. Therefore, in order to maintain the normal production of the gas well, the leakage rate of the plunger must be kept below the critical value.

3.4 Sensitivity Analysis of Single Displacement of Plunger to Gas Well Production

On the basis of the given basic parameters, according to the aforementioned constraints on the maximum lift flow pressure, lift air-to-water ratio, and daily gas production, the calculation is performed using the single discharge volume of gradient rise. Different single discharge volumes, to calculate the daily gas production of the gas well, so as to study and analyze the influence of a single liquid discharge on the production of the gas well. Some calculation results are shown in Table 6.

Table 6: Influence of single displacement of plunger on gas well production

Single discharge volume(m3)	Maximum flow pressure (MPa)	lift air-liquid ratio (m3/m3)	Shut-in time(min)	Gas production (m3)
0.5	6.561	509.766	75.61	3577.623
0.55	6.955	487.924	83.263	3493.259
0.6	7.347	469.593	92.021	3404.134
0.95	10.046	393.642	222.061	2615.686
1.0	10.429	387.069	265.515	2467.413
1.05	10.813	381.157	327.056	2301.672
1.1	11.198	375.832	421.387	2109.428

It can be seen from the table that after the single displacement of the plunger gradually increases, the maximum flow pressure of the gas well also gradually increases, and the shut-in time of the gas well gradually becomes longer. The specific analysis is shown in Figure 5.

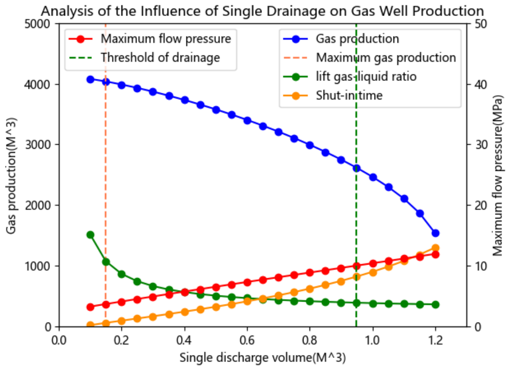

Figure 5: Sensitivity analysis diagram of single displacement of plunger to gas well production

It is not difficult to see from the figure that when the single liquid displacement of the plunger continues to increase, the maximum flow pressure of the gas well will be greater than the formation pressure, the shut-in and repressurization time will increase, and the production rate will decrease, which will eventually lead to an increase in the daily gas production of the gas well. Low. Therefore, in order to make the gas production of the gas well reach the set value, the single displacement of the plunger should be controlled at about the displacement corresponding to the set production, and the fluctuation range should be kept within a certain safe range.

4. Conclusion

(1) Based on the principle of plunger lifting and drainage for gas recovery, this study analyzes the distribution of fluid and pressure in the wellbore when the plunger ascends to start, when the plunger ascends to the wellhead, and when the well is shut down, and analyzes Mutual conversion relationship in the process of jetting flow and well shut-in and repressurization.

(2) Research and design of an optimization algorithm for plunger lift drainage and gas recovery, and set a set of basic parameters for digital simulation calculation based on the understanding of oil wells. Sensitivity analysis of plug single discharge volume to daily gas production of gas wells, and a graphical analysis was carried out.

The results show that based on the set parameters, the plunger lift optimization design algorithm can better analyze the influence of the plunger characteristic parameters on the gas well production, and realize the adjustment of the gas well production by adjusting the plunger parameters. It has certain application value for gas wells using plunger drainage gas production technology.

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