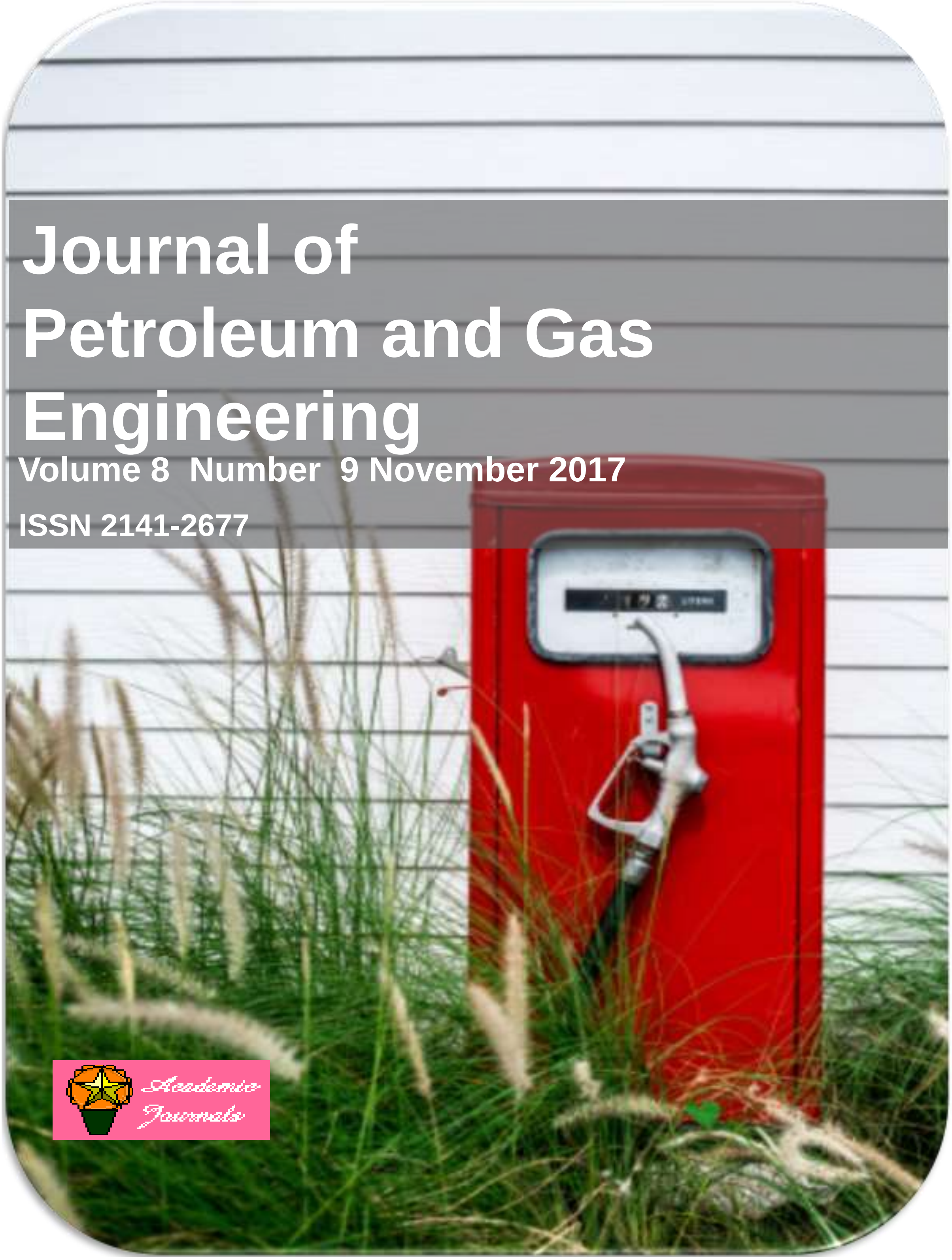

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Full Length Research

Dynamic simulation of the unloading process of gas-lift hard lifts in the Kelameili Water-Flooded Gas Well

Zhong Haiquan[1]*, Zhang Feng[2], Feng Dianfang[2], Wang Xiaolei[2], Wang Zhengming[2], Hong Jiangling[2] and Chen Wei[2]

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Owing to its strong adaptability and flexibility, gas lift is widely used in deliquification or production restoration for water-flooded gas well. This paper briefly introduced the advantages and adaptability of the gas-lift hard lift technology (gas lift without gas lift valve). The mathematical model based on the mass and momentum conservation was established to describe the unloading process of gas-lift hard lift and the finite difference method used to solve the model. Taking the DX180X water-flooded gas well in Kelameili Gas Field (located in Karamay City, Xinjiang, China) as example, the unloading process of gas lift hard lift was simulated. The influence factors, including the gas source of nitrogen gas or natural gas, the lifting channel of tubing lifting or annulus lifting, the kick-off pressure and operating injection pressure, were analyzed. The changes of the wellhead pressure and the bottomhole pressure during the unloading period were simulated. The results indicate that to reduce the kick-off pressure and liquid reflux, it is recommended that annulus lifting with nitrogen gas should be chosen. This study provides the technological guidance and method for the adaptable evaluation, the process design and the compressor selection for gas-lift hard lift.

Key words: Water-flooding well, gas lift, gas-lift hard lift technology, unloading process, mathematical model.

INTRODUCTION

Kelameili Gas Field is a volcanic gas reservoir of high porosity and extra-low permeability. It is characterized by the strong heterogeneity of the reservoir, the nonhomogeneous distribution of the fracture, and the complicated relationship between gas and water (Tang et al., 2010; Wang et al., 2014). Recently, the reducing production of gas wells results in liquid loading. With the increase of the loading quantity, some gas wells are flooded and shut down. A common method is using gas lift technology to unload the liquid and recover the production. By installing gas lift valves, the technology has a wide range of application conditions. However, it needs to replace the original production strings, or even inject the killing fluid (Jia et al., 2013; Wang, 2016), which may prolong the project period time and cause damage to the reservoir. By contrast, gas-lift hard lift technology (gas lift without gas lift valve) need not move the original production string or inject the killing fluid, which greatly shortens the project hours and avoids the risks of killing well. It directly injects the gas through annulus for tubing

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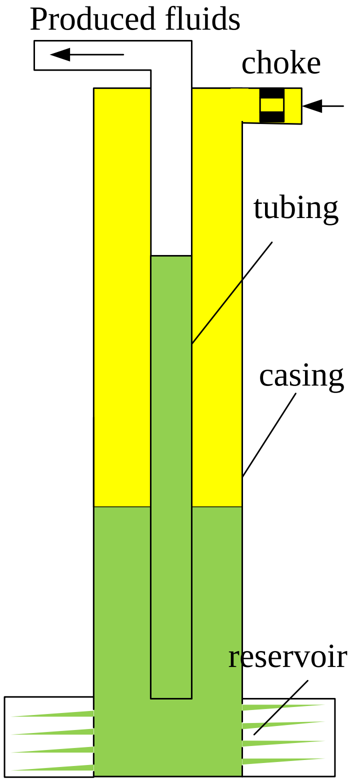

Figure 1. Liquid level drops in the annulus and liquid level rises in the tubing.

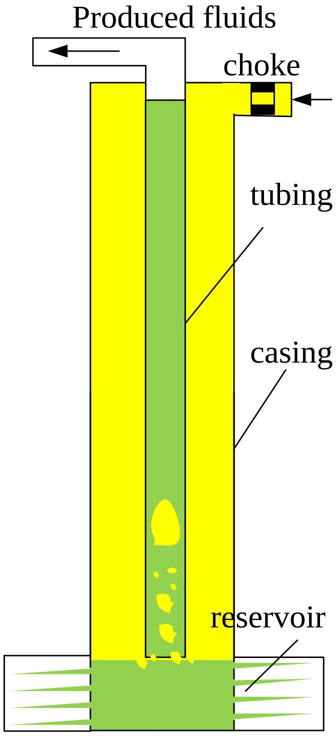

Figure 2. Gas-liquid two-phase pipe flow in the tubing.

lifting or injecting the gas through tubing for annulus lifting. However, the technology usually brings high kick-off pressure and may influence the safety of tubing and casing strings, especially for the deep wells, the wells with high formation pressure, or the wells with weak water-absorption ability.

This paper presents a mathematical model for unloading process of gas lift hard lift based on mass and momentum conservation. The model is solved by using the finite difference method. Taking the DX180X water-flooded gas well in Kelameili Gas field as example, the unloading process of gas lift hard lift was simulated. Then the influencing factors, including gas source, lifting passage, kick-off pressure and so on, were analyzed. The results provide the technological guidance for the adaptable evaluation; the process design and the compressor selection for gas lift hard lift.

MODEL ESTABLISHMENT

The unloading process of gas lift hard lift (take the tubing lifting for example, as shown in Figures 1 and 2) includes the gas and liquid down flow in the annulus between tubing and casing, the inflow and backflow between the wellbore and the formation, and the gas-liquid two-phase flow in the tubing. To facilitate the simulation, the following reasonable assumptions are made:

(1) The flow in the annulus is treated as one-dimensional flow. Gas and liquid do not mix in the annulus (Capucci and Serra, 1991; Tang et al., 1997; Liao et al., 2003; Li, 2006; Zhang, 2006).
(2) The temperature along the wellbore is simplified to a linear distribution.
(3) The wellhead tubing pressure is set as constant. The upstream pressure of the wellhead injection valve is set as constant.
(4) Liquid is incompressible.

Conservation of mass in tubing-casing annulus

Neglecting the annular air column gravity, according to the mass conservation, the changes of the wellhead casing pressure can be expressed as:

$$\left.\frac{dp}{dt}\right|_{surface} = \frac{1}{V_g \left.\frac{d\bar{\rho}_g}{dp}\right|_{surface}} \left(\rho_{gsc} Q_{gs} - \rho_{gsc} Q_{gi} - \bar{\rho}_g Q_{Li} \right) \tag{1}$$

Where Q_{gs} is the injected gas flux through the wellhead injection valve, m^3/s; Q_{gi} is the gas flux from the pipe shoe to the tubing, m^3/s (Q_{gi}=0 before the annular liquid level reaching the pipe shoe); Q_{Li} is the liquid flux from the annulus to the tubing and formation, m^3/s. (Q_{Li} =0 after the annular liquid level reaching the pipe shoe); ρ_{gsc} 、$\overline{\rho}_g$ is the standard gas density and the average gas density in annulus respectively, kg/m^3; V_g is the gas volume in the annulus, m^3; and p is the pressure,Pa; t is the time, s.

Inflow and backflow performance between the wellbore and formation

When the formation pressure $\overline{p_r}$ is higher than the bottom hole pressure p_{wf}, the fluid would flow toward the wellbore. For gas wells with liquid present, the liquid rate q_L can be calculated using the liquid production index PI:

$$q_L = PI \times \left(\overline{p_r} - p_{wf}\right) \tag{2}$$

The gas rate can be calculated according to the gas-liquid ratio of the formation. During the unloading process, the fluid would flow back to the formation when the bottom hole pressure p_{wf} is higher than the formation pressure $\overline{p_r}$. For the backflow, due to the irreversibility of the formation porous media, the amount of backflow is smaller than that of inflow at the same condition. It is assumed that the mechanistic of the backflow and the inflow is consistent. A backflow index η, the ratio of the backflow amount to the inflow amount at the same pressure drop condition, is defined. Then the backflow amount is calculated as:

$$q_{LB} = PI \times \left(p_{wf} - \overline{p_r}\right) \times \eta \tag{3}$$

Mass and momentum balances of two-phase flow in the tubing

Mass balances

The tubing is divided into N segments. The length of each segment is L. Then the mass balance is applied to the axial direction of the tubing (Tang et al., 1997). The mass conservation of the liquid phase is as follows:

$$\frac{\partial}{\partial t}\left(\rho_L H_L\right) + \frac{\partial}{\partial L}\left(\rho_L v_{SL}\right) = m_L \tag{4}$$

The mass conservation of the gas phase is as follows:

$$\frac{\partial}{\partial t}\left(\rho_G H_G\right) + \frac{\partial}{\partial L}\left(\rho_G v_{SG}\right) = m_G \tag{5}$$

Where H_L、H_G is the liquid holdup and the gas holdup, respectively, $H_L+H_G=1$; ρ_G, ρ_L is the gas density and the liquid density, respectively, kg/m^3; v_{sg}, v_{sL} is the gas superficial velocity and the liquid superficial velocity, respectively, m/s; and m_G, m_L is the gas mass-flux per volume and the liquid mass-flux per volume, respectively, $kg/(m^3 \cdot s)$.

Momentum balances

According to the momentum conservation of gas-liquid mixture, the equation can be obtained as follows:

$$\frac{\partial\left(\rho_G v_{SG} + \rho_L v_{SL}\right)}{\partial t} + \frac{\partial}{\partial L}\left(\frac{\rho_G v_{SG}\left|v_{SG}\right|}{H_G} + \frac{\rho_L v_{SL}\left|v_{SL}\right|}{H_L}\right) + \frac{\partial p}{\partial L} + \rho_m g \sin\theta + \left.\frac{\partial p}{\partial L}\right|_{fric} = 0 \tag{6}$$

Where ρ_m is the density of gas-liquid mixture, kg/m^3; $\left.\frac{\partial p}{\partial L}\right|_{fric}$ is the frictional pressure gradient, Pa/m; and θ is the deviation angle, deg.

Initial conditions and boundary conditions

In the initial condition, the water-flooded gas well is shut, the tubing and annulus are filled with a certain height of the liquid, and the bottom hole static pressure is approximately equal to the formation pressure. Give the initial conditions: the wellhead tubing pressure is p_t (Pa), the liquid height in the tubing is H_t (m), the wellhead casing pressure is p_c, the liquid height in the annulus is H_c (m), the formation pressure is $\overline{p_r}$ (Pa), and the depth of the producing layer is L_m(m),. The initial bottom hole static pressure can be expressed as:

$$\overline{p_r} = p_c e^{S_c} + \overline{\rho}_{Lc} g H_c \tag{7}$$

$$\overline{p_r} = p_t e^{S_t} + \overline{\rho}_{Lt} g H_t \tag{8}$$

Where $S_c = 0.03418\gamma_g\left(H_m - H_c\right) \Big/ \left(\overline{T_c}\,\overline{Z_c}\right)$, $S_t = 0.03418\gamma_g\left(H_m - H_t\right) \Big/ \left(\overline{T_t}\,\overline{Z_t}\right)$, $\overline{T_c}$,$\overline{T_t}$ is the average temperature of the static gas column in the annulus and that in the tubing respectively, ℃; $\overline{Z_c}$, $\overline{Z_t}$ is the average deviation factor of the static gas in the annulus and that in the tubing, respectively, dimensionless.

According to the known initial wellhead tubing pressure and wellhead casing pressure, the initial liquid height H_t and H_c can be determined by iteration based on Equations 7 and 8.

Before the gas enters the tubing, the annulus presents the plug flow. The tubing presents a single-liquid-phase flow under the liquid level and a single-gas-phase flow above the liquid level. After the gas entering the tubing, the gas-liquid two-phase flow is formed in the tubing, the pressure gradient and other associated parameters in the tubing can be calculated by the Hagedorn-Brown method (Hagedorn and Brown, 1965).

MODEL SOLUTION

The unloading process of gas-lift hard lift is divided into two stages.

The first stage: Only the liquid enters the tubing and formation from the annulus. In the tubing, the gas is in the upper section and the liquid is in the lower section. The gas-liquid mass conservation in the annulus (Equation 1) can be expressed as time difference equation. With the backflow equation, the model can be solved using iterating method.

The second stage: The injected gas mixes with a part of liquid in the tubing. The mixture density decreased gradually in the tubing. When the bottom hole pressure is reduced lower than the formation pressure, the gas and liquid begins to enter into the tubing from the formation. So the model is calculated by considering the time difference and the space difference of the tubing.

Difference form of mass balances

The space differential is written as backward Euler difference. The time differential is written as space center and time backward difference. The difference form of the Equations 4 and 5 are as follows:

$$\frac{(\rho_L H_L)_j^n + (\rho_L H_L)_{j-1}^n - (\rho_L H_L)_j^{n-1} - (\rho_L H_L)_{j-1}^{n-1}}{2\tau} + \frac{(\rho_L v_{SL})_j^n - (\rho_L v_{SL})_{j-1}^n}{h} = m_{Lj}^n \tag{9}$$

$$\frac{(\rho_g H_G)_j^n + (\rho_g H_G)_{j-1}^n - (\rho_g H_G)_j^{n-1} - (\rho_g H_G)_{j-1}^{n-1}}{2\tau} + \frac{(\rho_g v_{SG})_j^n - (\rho_g v_{SG})_{j-1}^n}{h} = m_{Gj}^n \tag{10}$$

Where *h* is the space step, m; τ is the time step, s; m_{Lj} is the mass flux of the liquid per volume in the *j* unit, kg/m^3·s, and m_{Gj} is the mass flux of the gas per volume in the *j* unit, kg/m^3·s, m_{Lj} and m_{Gj} is not zero only at the pipe shoe.

Difference form of momentum balances

The equation of momentum balances (Equation 6) is much more complex than the equation of mass balances of gas and liquid. The equation of mixture momentum conservation is divided into five parts. It includes the velocity item, the acceleration item, the gravity item, the friction item, and the total pressure gradient item. The difference format for each item is as follows:

The velocity item:

$$p_1 = \frac{\partial}{\partial t}\left(\rho_L v_{SL} + \rho_g v_{SG}\right) = \frac{1}{2\tau}\left[\left(\rho_L v_{SL} + \rho_g v_{SG}\right)_j^n + \left(\rho_L v_{SL} + \rho_g v_{SG}\right)_{j-1}^n - \left(\rho_L v_{SL} + \rho_g v_{SG}\right)_j^{n-1} - \left(\rho_L v_{SL} + \rho_g v_{SG}\right)_{j-1}^{n-1}\right] \tag{11}$$

The acceleration item:

$$p_2 = \frac{\partial}{\partial L}\left(\frac{\rho_L v_{SL}\left|v_{SL}\right|}{H_L} + \frac{\rho_g v_{SG}\left|v_{SG}\right|}{H_G}\right) = \frac{1}{h}\left[\left(\frac{\rho_L v_{SL}\left|v_{SL}\right|}{H_L} + \frac{\rho_g v_{SG}\left|v_{SG}\right|}{H_G}\right)_j^n - \left(\frac{\rho_L v_{SL}\left|v_{SL}\right|}{H_L} + \frac{\rho_g v_{SG}\left|v_{SG}\right|}{H_G}\right)_{j-1}^n\right] \tag{12}$$

The gravity item:

$$p_3 = \frac{g\sin(\theta)}{2}\left[\left(\rho_L H_L + \rho_g H_G\right)\Big|_j^n + \left(\rho_L H_L + \rho_g H_G\right)\Big|_{j-1}^n\right] \tag{13}$$

The friction item:

$$p_4 = \frac{1}{2}\left\{\left(\frac{dp}{dL}\Big|_{fric}\right)_j^n + \left(\frac{dp}{dL}\Big|_{fric}\right)_{j-1}^n\right\} \tag{14}$$

The total pressure gradient backward difference:

$$p_5 = \frac{dp}{dL} = \frac{p_j^n - p_{j-1}^n}{h} \tag{15}$$

Thus, the pressure at the time section n and the nodal section *j* is expressed as:

$$p_j^n = p_{j-1}^n - h\left(p_1 + p_2 + p_3 + p_4\right) \tag{16}$$

According to the difference equations from Equations 9 to 16, the Newton-Rafson method is used to obtain the solution of the difference equations.

CASE SIMULATION AND DISCUSSION

The well DX180X is shut-in because of the liquid loading. Before gas lifting, the static liquid level in the tubing and annulus is about 1884 m (the tubing pressure and the casing pressure are all about 14 MPa). The well's basic data are as follows: the size of the production casing is 139.7 mm (inner diameter is 121 mm), the size of the tubing is 73 mm (inner diameter is 62 mm), the depth of the tubing shoe is 3548.87 m, the middle depth of the layer is 3570m, the depth of the artificial bottom hole is 3740 m, the formation static pressure is 32 MPa, the liquid production index is about 1 m^3/d·MPa. Before liquid

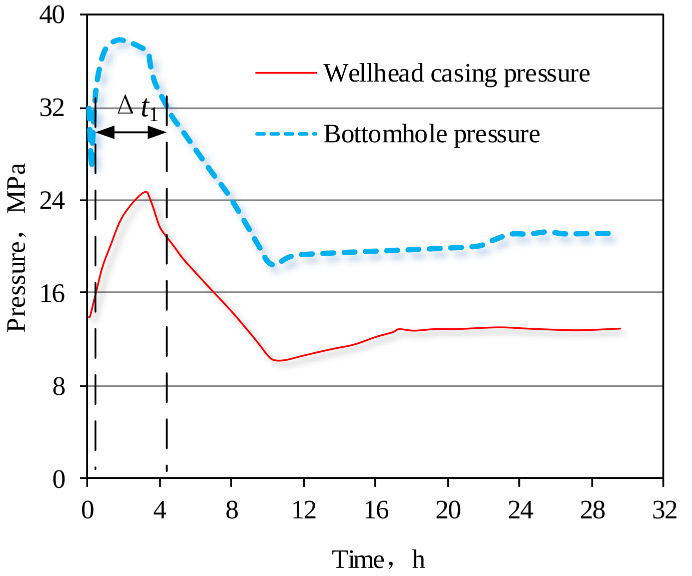

Figure 3. The gas-lift unloading process (kick-off pressure is 25 MPa).

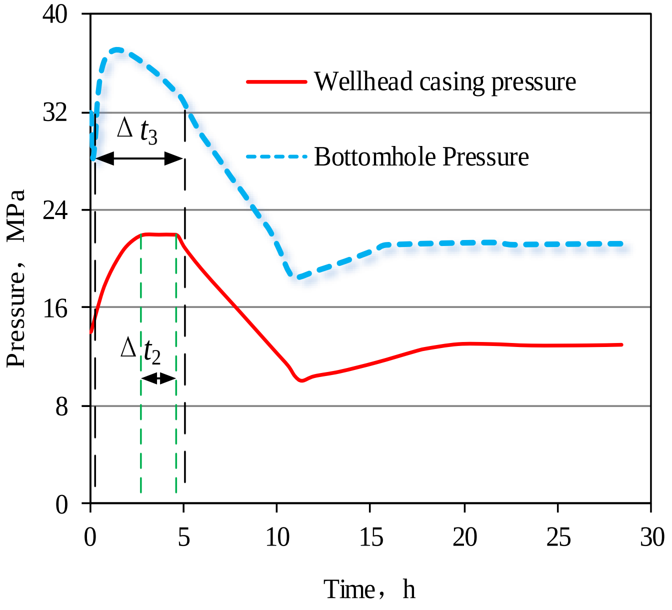

Figure 4. The gas-lift unloading process (kick-off pressure is 22 MPa).

loading, the gas-liquid ratio is about 2600 m^3/m^3, the gas production is about 2.5 × 10^4 m^3/d. Due to the well connecting to the high pressure gathering pipelines, the wellhead tubing pressure is increased to 9 MPa.

Unloading with nitrogen gas

The kick-off pressure is 25 MPa (the maximum gas injection pressure), the maximum gas injection flux is 4 × 10^4 m^3/day. The unloading method of tubing lifting (injecting gas through annulus) is adopted. Both the unloading wellhead tubing pressure and the producing wellhead tubing pressure are 9 MPa. The backflow coefficient is set at 0.6. The change of the wellhead casing pressure and the bottom hole pressure during the unloading process is as shown in Figure 3. The wellhead casing pressure first increases and then decreases, and finally increases slightly to reach stability. The first increase of the pressure is because: before the annular liquid level reaches the pipe shoe, the wellhead casing pressure increases with the injection gas increasing. When the annular liquid level reaches the pipe shoe, the casing pressure would reach the maximum (24.8 MPa). After that, gas enters the tubing and the casing pressure drops to the minimum. Finally, the casing pressure increases slightly because the formation liquid increases the liquid level of the tubing. The bottom hole pressure decrease when opening the well is due to a sudden drop of the wellhead tubing pressure (from 14 MPa to 9 MPa). During the time period Δt_1 (about 4 h), the bottom hole pressure is higher than formation pressure, so the wellbore fluid flows to the formation. After unloading, the injection gas flux is 2.5 × 10^4 m^3/d (neglect the gas from the formation), the injection pressure is 12.68 MPa, and the duration time of the unloading is about 20 h.

If the kick-off pressure is reduced to 22 MPa, other parameters are the same. The change of the wellhead casing pressure and the bottom hole pressure during the unloading process is as shown in Figure 4. The wellhead casing pressure first increases and then maintains 22 MPa for a long time Δt_2 (about 2 h). The gas cannot be injected into the wellbore. The wellbore builds the pressure and presses the liquid into the formation. It is indicated that the kick-off pressure can hardly decrease unless the building time is increased. During the time period Δt_3 (about 5 h), the bottom hole pressure is higher than the formation pressure, and the wellbore fluid flows to the formation. Figures 3 and 4 show that: The kick-off pressure is the key to the unloading of gas-lift hard lift. If the kick-off pressure is too low, the well would not unload, and obviously prolong the duration time of the liquid backflow to the formation. To reduce the possible damage of the backflow, the gas kick-off pressure should be as high as possible.

Unloading with natural gas

By switch the nitrogen gas to the natural gas, other input parameters are unchanged. The unloading method of tubing lifting (injecting gas through annulus) is adopted. The change of the wellhead casing pressure and the bottom hole pressure during the unloading process is as shown in Figure 5. The wellhead tubing pressure first increases and then maintain 25 MPa for a long time Δt_4

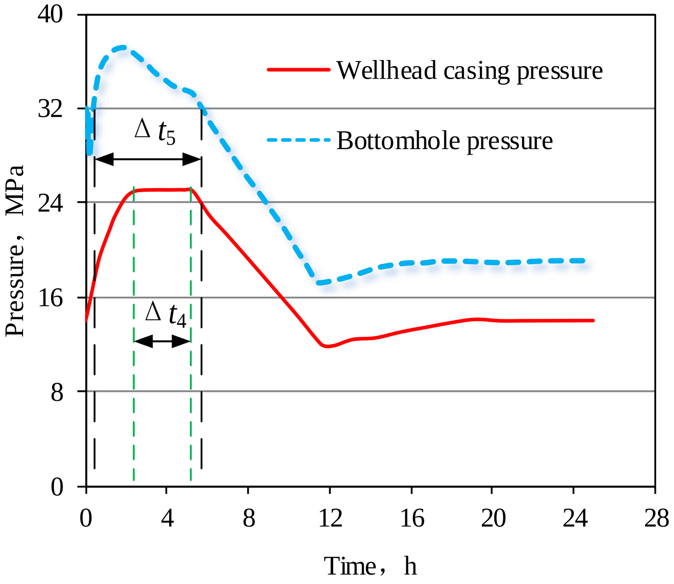

Figure 5. the gas-lift unloading process (injecting through annulus).

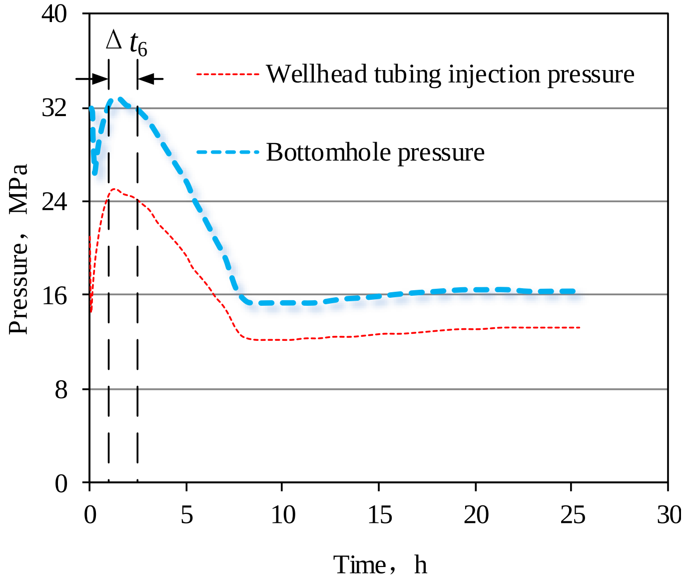

Figure 6. The gas-lift unloading process (through tubing).

(about 3 h). The gas cannot be injected into the wellbore. The wellbore builds the pressure and presses the liquid into the formation. It is indicated that the kick-off pressure can hardly decrease unless the building time increases. During the time period Δt_5 (about 5.4 h), the bottom hole pressure is higher than the formation pressure, and the wellbore fluid flows to the formation. After unloading, the injection gas flux is 3.0×10^4 m^3/d (it is higher than the gas production before water-flooded, so it is difficult to recover flowing production; to solve this problem, the wellhead tubing pressure should be reduced), the injection pressure is 14.0 MPa, and the duration time of the unloading is about 21 h.

If the unloading method of annulus lifting (injecting gas through tubing) is adopted, after which the gas lift method rapidly convert to injecting gas through annulus for tubing lifting, the change of the wellhead tubing pressure and the bottom hole pressure during the unloading process is as shown in Figure 6. After opening the well, the tubing liquid enters into the annulus quickly and the liquid level reaches the pipe shoe soon, which leads to the bottom hole pressure decreasing rapidly. During the time period Δt_6 (about 1.4 h), the bottom hole pressure is slightly higher than the formation pressure, and only a few wellbore fluids flows back to the formation, which has less damages to the formation. The maximum kick-off pressure is about 25 MPa, and there is no pressure building phenomenon. If the building pressure time is prolonged, the kick-off pressure would be further reduced.

Conclusions

(1) For the water-flooded well, gas-lift hard lift technology (gas lift without gas lift valve) need not move the original production string or inject the killing fluid. It can unload liquid by directly injecting gas through annulus for tubing lifting or injecting gas through tubing for annulus lifting, which greatly shortens the project hours and avoids the risks of killing the well.

(2) The mathematical model based on mass and momentum conservation was established to describe the unloading process of gas lift hard lift, with the finite difference method used to solve the model.

(3) Take the well DX180X as example, the influence factors, including the gas source of nitrogen gas or natural gas, the lifting channel of tubing lifting or annulus lifting, the kick-off pressure etc, are analyzed. The results indicate that the kick-off pressure using nitrogen gas is lower than that using natural gas at the same conditions. The kick-off pressure can be reduced by annulus lifting with tubing injecting. To reduce the possible damage of the liquid backflow to the formation, the maximum gas injection pressure should be as high as possible, or adopting the unloading method of annulus lifting.

(4) This study provides the technological guidance and method for the adaptable evaluation; the process design and the compressor selection for gas lift hard lift. Compared with the previous empirical method, the method used to determine the parameters is more accurate and reliable.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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