Study on the Minimum Flowing Pressure Boundaries of Different Reservoirs in SZ Development Zone

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Abstract. Reasonable bottom-hole flow pressure is the guarantee for giving full play to oil well productivity and improving oilfield development efficiency. In the actual production process of the oilfield, when the bottom hole flow pressure is reduced to a certain extent, the liquid production of the oil well start to decrease, and there exist a maximum production point in the oil well. To study the minimum bottom-hole pressure limits of different water cut stages in SZ development zone, the inflow dynamic analysis model of oil well is put forward. By considering the influence factors of bottom hole flow pressure change, such as water cut, dissolved gas coefficient, saturation pressure and formation pressure change, the minimum allowable bottom hole flow pressure of SP oil layer is 1.5 -2 MPa, and GTZ oil layer is 2 -2.5 MPa. The proposed boundary model of bottom hole flow pressure provides theoretical guidance for reasonable flow pressure design and production allocation of oil wells.

Keywords: flowing pressure; inflow performance curve; water cut.

1. Introduction
The study of reasonable flow pressure in an oilfield is an important proposition. The reasonable bottomhole flow pressure of an oil well is greatly related to the oil production, water production, development period, oilfield service life, limit setting of development indicators and huge economic benefits generated in the process of oilfield development [1-2]. Determining the bottom hole pressure limit during oilfield production plays an important role in enhancing oil recovery, reducing water consumption and reducing casing damage rate. There are many methods to research reasonable bottom hole flow pressure. In 1930, Evinger and Muskat[3] and other scholars started to research the working conditions of producing wells. It is concluded that the linear relationship between production and pressure in the seepage equation of gas-liquid two-phase seepage is changed into a curve relationship. In 1992, Wiggns[4] solved several quasi-steady equations of oil-gas seepage through Tailor's formula, and obtained the inflow performance equation of multiphase flow (oil-gas two-phase flow), which was an important turning point in the history of oil well research. Domestic scholars (Xu Yuangang, 2005; Jia Zhenqi, 2006; He Yanfeng, 2007) [5-7] established the inflow performance equation of low permeability reservoir considering the start-up pressure gradient, and based on the calculation proposed by Muskat and Evinger, gave the Darcy equation of quasi-stable nonlinear flow IPR curve dynamics. However, a large number of development practices and indoor studies show [8-9] that the ultra-low
permeability reservoir has both stress sensitivity and start-up pressure gradient, and it is not consistent with the actual seepage law to consider either of them. (Cogan, 2007; Liang Zhongqing, 2009; Li-ping jiang, 2011), [10-12] considering start-up pressure gradient and pressure sensitive effect deformation is proposed for low permeability reservoir non-darcy seepage equation at the same time, but also to have certain limitations, because when the bottom hole flowing pressure drop to below the saturation pressure, dissolved gas separation of crude oil viscosity increases sharply and relatively liquid percolation ability will reduce rapidly, the production capacity of low permeability reservoir has a significant impact. The traditional rational flow pressure calculation focuses on the relationship between flow pressure and production in different wells, but does not consider the changes of the minimum bottom hole flow pressure limits in different water content stage. In this paper, the reasonable flow pressure limit of water flooding in SP reservoir and GTZ reservoir in the extra-high water content stage of SZ development zone is studied, the development index variation trend of the oilfield in the extra-high water content stage is studied, and the minimum flow pressure limit of the water-content stage is determined, which is of great significance for guiding the pressure system adjustment in the future.

2. The Flowing Pressure Boundaries model

The principle of determining the lower limit of reasonable flowing pressure is to pay special attention to the influence caused by the change of crude oil physical properties in the method of flowing pressure drop, so that the lower limit of reasonable flowing pressure can ensure the maximum oil flow into the well and the maximum oil production.

(1) The Boundaries of flowing pressure model of considering the maximum liquid supply of formation

Wang Junkui, a senior engineer in Daqing Oilfield [13-14], established a new type of well inflow performance curve equation, which can be used to calculate the inflow performance of oil wells under different flow pressures.

The flow dynamic equation of the liquid phase is:

\[
q_L = \frac{J_o}{1 + (1 - f_w)R}(P_R - P_{of})
\]  

(1)

It can be seen from the equation that the main reason for the maximum production point is that after the flow pressure drops to a certain level, there may be two-phase flow of oil and gas near the bottom of the well, which makes the flow capacity of the oil phase drop sharply, and the contribution of the production pressure difference to the production has been Less than the impact of the decline in oil production index on production.

The flow pressure corresponding to the maximum production point on the flow dynamic curve, The equation (1) finds the first derivative and sets it to zero to obtain the minimum allowable flow pressure equation:

\[
\beta^2 J_o P_{of}^2 + 2(a - c_f)(a - \beta p_b) + J_o P_{of}^2 + (3b f_w + a p_o) \beta^2 + J_o P_{of}^2 + 2b f_w J_o (a - \beta p_b) P_{of} - a f_w J_o = 0
\]

In the equation: 
\[
a = B_b - \beta p_b; \quad b = \frac{1}{\rho_o}; \quad c = \frac{1}{\rho_o}; \quad \beta = 0.1033 \frac{ZT}{293}
\]

Through the SZ development zone actual data data verification, \( \beta \) as 10-3 magnitude parameter and \( \beta(p_b - p_{of}) \ll B_b \). For this reason, the first and second terms of the equation can be ignored, the equation is simplified, and the lowest bottom hole flowing pressure prediction equation is finally obtained.

\[
P_{of}^2 = \frac{1}{1 - n} \left[ \sqrt{n^2 P_b^2 + n(1 - n) P_b P_R - n P_b} \right]
\]

\[
n = \frac{0.1033 RT (1 - f_w)}{293.15 B_b}
\]  

(2)
The formula (2) can be used to determine the minimum allowable flow pressure of the oil well under different formation pressures and water cuts when the oil well obtains the maximum liquid production rate, which can be used as the basis for the oil well to schedule production. Comprehensive analysis of the inflow dynamic equation theoretically affirms that before and after the bubble point pressure, the flow capacity of the fluid presents a different trend with the decrease of the flow pressure. Before the flow pressure is greater than the bubble point pressure, as the flow pressure decreases, the liquid production index shows an upward trend; when the flow pressure is less than the bubble point pressure, as the flow pressure decreases, the liquid production index also shows a downward trend.

(2) The Boundaries of flowing pressure model of considering the depth of the pump

When the bottom hole flow pressure is lower than the saturation pressure, degassing near the bottom of the well affects the pump efficiency. Therefore, a reasonable bottom hole flow pressure must not only ensure the maximum liquid production, but also ensure that the free gas at the pump inlet does not exceed the required free gas flow. When there is a three-phase flow of oil, gas and water in the wellbore, the energy balance equation from the mixed gas flow:

\[
10 \int p \frac{1}{\rho} dp - \Delta H + h_w = 0
\]

(3)

The calculation formula of the pressure gradient under different water cut and different pressure in the wellbore of oil well is as follows:

\[
\frac{dp}{dH} = 0.1 \rho + 0.4425 f \frac{q^2}{\rho d_3}
\]

(4)

Substituting the actual parameters of the mine into the equation (4), the pressure gradient of the wellbore under different water cuts and pressures can be obtained. By applying multiple nonlinear regression analysis, a simpler pressure gradient calculation formula can be obtained:

\[
\frac{dp}{dH} = A + B \ln P_p
\]

(4)

In the equation: \( A = \sum_{j=1}^{3} a_j f \); \( B = \sum_{j=1}^{3} b_j f \)

From equation (5), after knowing the reasonable pump port pressure, pumping depth (Hm) and the middle depth of the reservoir (Hr), the reasonable bottom hole flow pressure can be calculated from the following equation

\[
P_{of_{\text{min}}} = p_p + 0.1 \times (A + B \ln 10 p_p)(H_m - H_p)
\]

(6)

\[
A = a_0 + a_1 f_w + a_2 f_w^2 + a_3 f_w^3
\]

\[
B = b_0 + b_1 f_w + b_2 f_w^2 + b_3 f_w^3
\]

Formula (6) is used to calculate the lower limit of flow pressure at different pumping depths and different water cuts in various development areas of the oilfield.

3. Main factors affecting the change of flow pressure

The second type reservoir in the SZ development zone is a typical low-permeability oil field, and the original driving type is elastic dissolved gas flooding. Therefore, when determining the reasonable flow pressure limit of an oil well, full consideration should be given to the reservoir fluidity factor. According to the oil well inflow dynamic equation during oil-gas-water three-phase seepage, comprehensively analyze the relevant factors that affect the minimum bottom hole pressure limit.

Calculate the lower limit of flow pressure under the influence of single factor by formula (1). Consider 4 factors, water content, dissolved gas coefficient, saturation pressure, formation pressure.

(1) Influence of moisture content

The lower limit of flow pressure corresponding to the water content of 85%, 90%, 93%, 95%, and 98% was studied respectively. As shown in the figure, the same formation pressure and different water
cut stages require different flow pressures. As the water cut increases, the lower limit of the flow pressure of the oil well decreases.

![Fig. 1 Effect of water content on convective pressure](image1)

(2) Influence of dissolved gas coefficient of crude oil

The water content is set at 93%, other conditions remain unchanged, and the dissolved gas coefficient of crude oil is changed. The lower limits of flow pressure were studied when the dissolved gas coefficients were 2, 4, 6, 8 and 10, respectively. As shown in the figure, the lower limit of flowing pressure increases with the increase of dissolved gas coefficient.

![Fig. 2 Effect of dissolved gas coefficient on lower limit of convective pressure](image2)

(3) Influence of saturation pressure

The water content is 93%, other conditions remain unchanged, change the saturation pressure. The lower limits of flow pressure at the saturation pressures of 7, 8, 9, 10 and 11 MPa were studied. The effect of saturation pressure and reasonable flowing pressure on production is independent of saturation pressure.

![Fig. 3 Effect of saturation pressure on lower limit of convective pressure](image3)

(4) Influence of formation pressure
The water cut is set at 93%, other conditions remain unchanged, and the formation pressure is changed. The lower limit of flowing pressure under the formation pressure of 8, 9, 10, 11 and 12 MPa is studied. When the formation pressure is greater than the saturation pressure, the correlation between formation pressure and formation size is weak.

![Fig. 4 Effect of formation pressure on lower limit of convective pressure](image)

4. The Minimum Flowing Pressure Boundaries in SZ Development Zone

Combined with the actual situation in the field, the lower limit of flow pressure is studied by the two methods: method one: considering the reservoir liquid supply, the maximum fluid supply of the formation is studied, that is, the lower limit of flow pressure is determined by Wang Junkui senior engineer in Daqing Oilfield according to the dynamic equation of oil and gas water flowing in three-phase seepage; method 2: consider the pump down depth to determine the lower limit of flow pressure;

(1) Boundary 1: from the point of view of formation fluid supply, study the maximum fluid supply of formation

Based on the inflow performance equation (2) of three-phase oil gas water flow, the lower limit of flowing pressure in different water cut stages is calculated by inflow performance method according to the actual development data of different oil layers. The actual parameters are as follows:

| parameter | Value | parameter | Value |
|-----------|-------|-----------|-------|
| $F_w$ (%) | 93.65 | $B_o$ | 1.12 |
| $P_R$ (Mpa) | 9.17 | $R m^3/(m^3\cdot MPa)$ | 4.33 |
| $P_b$ (Mpa) | 9.0 | $T$ (K) | 315.4 |

According to the current development situation of Sapu reservoir, the lower limit of flowing pressure at different water cut stages is calculated by inflow performance method, as shown in Figure 2.5. Under the current conditions, the lower limit of flowing pressure decreases with the increase of water cut. Based on the calculation of 93% water cut at present, the minimum bottom hole flowing pressure of SP reservoir well pattern is 1.37mpa, and that of GTZ reservoir well pattern is 1.27mpa

![Fig. 5 Relationship between lower limit of flowing pressure and water cut in different oil layers](image)
(2) Boundary 2: study the influence of flow pressure on pump efficiency from the perspective of pump discharge

According to the physical parameters of SP reservoir, the flowing pressure is calculated by formula (6).

| Table 2. Determination of actual reservoir parameters |
|------------------------------------------|-----|-----|-----|-----|-----|-----|
| a0       | a1  | a2  | a3  | oil layer | f_w | H_m,m | H_p,m |
| -0.048   | 0.064 | -0.014 | 0.099 | oil layer | f_w | H_m,m | H_p,m |
| b0       | b1  | b2  | b3  | SP       | 0.93 | 930   | 800   |
| 0.029    | -0.011 | 0.004 | -0.022 | GTZ     | 0.93 | 1100  | 950   |

The depth of the pump has a great influence on the lower limit of the convective pressure. At present, the lower limit of flow pressure increases with the increase of water cut. The minimum bottom hole flowing pressure of SP reservoir is 1.81Mpa, and that of GTZ reservoir is 2.18mpa.

![Fig. 6 Relationship between lower limit of flowing pressure and pump depth in different reservoirs](image)

### 5. Conclusion

In view of the situation that the oil well production has gradually decreased since the second type water drive oil layer in saszhong development zone is put into operation, the water content rises rapidly and the gas production is large. Considering the influence of the oil degassing and the permeability change of the reservoir, the dynamic equation of oil well inflow is established. According to the equation, the minimum allowable flow pressure of the oil well corresponding to the largest oil production point can be obtained.

According to the actual production data of the oilfield, it is clear that the minimum allowable bottom flow pressure of the oil well in Sapu reservoir is between 1.5-2 MPa; the minimum allowable bottom flow pressure of high platform oil reservoir is between 2-2.5 MPa. To determine the reasonable bottom hole flow pressure of oil well should be controlled near the minimum allowable flow pressure, so as to reduce the bottom hole flow pressure too low, which is not conducive to the normal production capacity of the well, and the phenomenon of rapid rise of water content and degassing of oil well occurs during the production process.

**Physical meaning of parameters in equation**

- $B_o$ - Volume coefficient of crude oil under saturation pressure;
- $B_s$ - Volume coefficient of crude oil;
- $f_o$ - Oil cut;
- $f_w$ - Water cut;
- $J_L$ - Liquid production index, MPa;
- $J_o$ - Oil production index, MPa;
- $p_f$ - Formation pressure, MPa;
- $p_{wf}$ - Bottom hole flowing pressure, Mpa;
- $p_o$ - Oil production at saturation pressure, t/d;
- $q_o$ - Oil production of oil well, t/d;
- $R$ - Gas-oil ratio of downhole oil layer, m³/m³;
- $T$ - Bottom hole oil layer temperature, oK;
- $Z$ - Deviation coefficient of natural gas;
- $\alpha$ - Solubility coefficient of crude oil, m³/m³·MPa;
- $\beta$ - Change rate of crude oil volume coefficient, m³/MPa;
- $H_m$ - Middle depth of
reservoir, m; Hp-Pump depth, m; a0, a1, a2, a3, b0, b1, b2, b3-regression coefficient, with different values in each development zone.

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