Determination of reasonable water injection timing for complex fault block high saturation reservoir - A case study of C30 fault block in Chaheji oilfield

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Abstract. High saturation reservoir has the characteristics of high gas-oil ratio, high saturation pressure and low difference between reservoir pressure and saturation pressure. In the process of development, the oil layer is very easy to degas due to the lag of water injection, which affects the production of oil well. Therefore, it is necessary to determine reasonable water injection timing and timely water injection to ensure the efficient development of high saturation reservoir. Based on the characteristics of complex fault block high saturation reservoir, the reasonable water injection timing of high saturation reservoir is determined by means of the combination of the finite layer quasi-steady state well test method and the material balance method. Through the actual production data verification, the calculation results of two methods are approximate, and the accuracy is high enough to meet the production need. The determination method is suitable for the reasonable injection timing of high saturation reservoir.

1. Preface
Compared with ordinary black oil reservoir, high saturation reservoir has the characteristics of good oil quality, high gas-oil ratio, high saturation pressure and low difference between reservoir pressure and saturation pressure. When the reservoir pressure stays above the saturation pressure, the properties of the reservoir will not change and gas will not degas from oil layer. It is advantageous to the flow of oil in the formation, which improves the production capacity of oil well. When the reservoir pressure is lower than the saturation pressure, the properties of the reservoir will change and gas will degas from oil layer seriously. At this time, the flow of oil in the formation will get very strong resistance, which reduces the oil recovery rate greatly [1-3]. In addition, the large decrease of pore pressure in reservoir will lead to a sharp decrease of permeability, which significantly reduces the fluid production index and oil production index of oilfield [4-5]. Therefore, it is necessary to determine reasonable water injection timing and recharge formation energy in time. For high saturation reservoir, it is generally required that the bottom hole flowing pressure $P_{orf}$ is greater than the saturation pressure $P_h$. When the bottom hole flowing pressure drops to the saturation pressure, the corresponding exploitation time is the reasonable water injection timing of the reservoir [6].

The high saturation reservoir of C30 complex fault block is a step fault zone complicated by faults, the oil sand body is fragmented, the average reservoir pressure is 29.5MPa, the saturation pressure is 21.2MPa, the average porosity is 19%, and the air permeability is 111mD, which is the reservoir of
middle permeability and middle porosity. The reservoir enrichment degree is controlled by double factors of lithology and structure, which is mainly the underwater distributary channel of shallow water delta facies sedimentary environment. The oil sand body development is fragmented and the oil-bearing area is small, so it is different from the traditional seepage mechanism of the homogeneous reservoir with large oil bearing area. In this paper, the reasonable water injection timing is determined by the quasi-steady state well test method which is suitable for small oil bearing area and the material balance method which has determined the production pressure difference \([7,8]\). Through the actual production data verification, the calculation results of two methods are approximate and high accurate, which can meet the need of production. The determination method is suitable for the reasonable injection timing of high saturation reservoir.

2. Quasi-steady state well test method

In the process of actual production, there is no real infinite layer. When the well test time is longer in complex fault block reservoir, the characteristics of deviating unsteady seepage flow will appear in later stage of both pressure drop well test and pressure recovery well test. And the pressure characteristics of transition section and quasi steady state are displayed. The reservoir boundary can be divided into the boundary with no fluid passing and the boundary with fluid passing. The boundary with no fluid passing is generally regarded as the fault boundary, closed boundary, and pinchout boundary. The oil-water boundary is often used as the constant pressure boundary with the fluid passing. In addition, if the reservoir area is larger and there is more than one production well, the test well is in a limited range of oil drainage area influenced by other production wells. Then the test well can be used as a bounded layer analysis.

2.1. Method principle of quasi-steady state well test

It is known from the seepage mechanics that the relationship between average pressure and bottom hole flowing pressure of reservoir in the quasi steady flow stage is as follows:

\[
\bar{P} - P_{wf}(t) = \frac{2.121 \times 10^{-3} \times \mu B}{k h} (\lg \frac{4\pi e^2 \gamma r_w^2}{4\pi h^3} + 0.8686 s)
\] (1)

In the formula, the oil drainage area is \(A = \pi r_w^2\), \(4\pi e^2 = 56.31857 = 31.6206\), \(\gamma = 1.781\).

In general, the oil drainage area is not circular, the shape factor \(C_A\) is substituted for \(31.6206\), and the influence of boundary shape is considered as follows:

\[
\bar{P} - P_{wf}(t) = \frac{2.121 \times 10^{-3} \times \mu B}{k h} (\lg \frac{4A}{\gamma C_A h r_w^2} + 0.8686 s)
\] (2)

The principle of material balance: \(q t B = 24\pi e^2 \phi (p_i - p) C_i\):

\[
\bar{p} - P_{wf}(t) = \frac{2.121 \times 10^{-3} \times \mu B}{k h} (\frac{q t B}{24\pi e^2 \phi} h C_i)
\] (3)

Simultaneous equation (2), equation (3) and \(\eta = \frac{k}{\phi \mu C_i}\):

\[
P_i - P_{wf}(t) = \frac{2.121 \times 10^{-3} \times \mu B}{k h} (\frac{4A}{\gamma C_A h r_w^2} + \frac{14.4 \pi \eta t}{2.303 A} + 0.8686 s)
\] (4)

According to the equation (4), the bottom hole flowing pressure at arbitrary time is:

\[
P_{wf}(t) = P_i - \frac{2.121 \times 10^{-3} \times \mu B}{k h} (\frac{4A}{\gamma C_A h r_w^2} + \frac{14.4 \pi \eta t}{2.303 A} + 0.8686 s)
\] (5)

According to equation (5), the reasonable water injection timing of reservoir is obtained when the bottom hole flowing pressure \(P_{wf}\) reaches the saturation pressure \(P_b\).
\[ t = \left( P_i - P_b \right) \frac{k h}{2.121 \times 10^{-3} \mu B} \log_{10} \left( \frac{4A}{\gamma C_A r_w} \right) - 0.8686 \frac{1}{s} \left( \frac{2.303A}{14.4\pi \eta} \right) \]  

In the formula: \( P_i \) - initial formation pressure, Mpa; \( P_b \) - saturation pressure, Mpa; \( P_{wf}(t) \) - bottom hole flowing pressure at t moment, Mpa; \( Q \) - surface production of oil well, m\(^3\)/d; \( \mu \) - the viscosity of fluid, mPa.s; \( B \) - volume coefficient of fluid; \( k \) - permeability of formation, um\(^2\); \( h \) - thickness of oil layer, m; \( r_w \) - the radius of the well, m; \( A \) - oil drainage area, m\(^2\); \( \gamma \) - euler constant; \( C_A \) - shape factor of single well drainage area; \( \eta \) - the diffusivity coefficient of the formation; \( C_t \) - total compression coefficient of reservoir, MPa\(^{-1}\); \( s \) - skin coefficient; \( t \) - the time from well open up, h.

2.2. The reasonable water injection timing calculation of quasi-steady state well test

The reasonable water injection timing is obtained when the bottom hole flowing pressure drops to the saturation pressure. According to the actual geologic conditions of C30 fault block, the effective thickness of oil layer is 10m and the initial average single well output is 10t/d. The numerical model of well testing software module is selected. Then the bounded circular homogeneous reservoir is established. The simulative reasonable water injection timing is forecasted by taking different well output and different drainage area radius. From the simulation result of formation pressure change process in figure 1, the smaller the drainage area radius, the faster the formation pressure declines; the greater the drainage area radius, the slower the formation pressure declines.

![Figure 1. The formation pressure drop of elastic development period](image1)

![Figure 2. The relationship between well output and reasonable water injection timing](image2)
It can be seen from the numerical simulation results of quasi-steady state well test method, the relationship between the oil well output and the reasonable water injection timing of different well control radius is obtained. The greater well control radius and lower well output lead to more time of the bottom hole flowing pressure reaching the saturation pressure. As can be seen from figure 2, the reasonable water injection timing is 3.3 months in drainage area radius of 150m.

3. Material balance method

In order to research the calculation method of reasonable water injection timing through multiple perspectives and multiple methods, the material balance method is used to determine the reasonable water injection timing. The method is applied in the condition of the reservoir production pressure drop has been known.

3.1. Method principle of material balance method

Firstly, the geological reserves in the drainage area are calculated. And then the cumulative oil production of single oil well, the time needed for the bottom hole flowing pressure drop to the reservoir saturation pressure is calculated, and the reasonable water injection timing is determined. For the reservoir of $P_t>P_o$, the equation of material balance is as follows:

$$NB_{oi}C_{eff}\Delta p = N_pB_o - (W_e + W_i - W_p)B_v$$

(7)

In the early stage of elastic development, the oil well does not contain water, so $W_e=0$, $W_i=0$, $W_p=0$, it can be obtained by equation (7):

$$NB_{oi}C_{eff}\Delta p = N_pB_o$$

(8)

$$N_p = \frac{NB_{oi}C_{eff}\Delta p}{B_o}$$

(9)

Because the average pressure of the reservoir is the sum of the bottom hole flowing pressure and the production pressure drop, it can be obtained by equation (10):

$$p = p_{sat} + \Delta p_s$$

(10)

The reservoir pressure drop is as follows:

$$\Delta p = p_i - (p_{sat} + \Delta p_s)$$

(11)

According to the calculation formula of reserves, the geologic reserves calculation formula of single well control range is as follows:

$$N = \frac{A h \phi S_o}{B_{oi}} \rho$$

(12)

Simultaneous equation (9) and equation (12):

$$N_p = \frac{A h \phi S_o \rho C_{eff} \Delta p}{B_o}$$

(13)

According to the cumulative oil production formula of single oil well:

$$10000 = q t$$

(14)

Reasonable water injection timing is obtained:

$$t = \frac{10000 A h \phi S_{oi} \rho C_{eff} \Delta p}{B_o q}$$

(15)

In the formula, $N$- geological reserves of petroleum, $10^4$t; $N_p$- cumulative oil production, $10^4$t; $B_{oi}$- original crude oil volume coefficient, dimensionless; $B_{o}$- current volume coefficient of crude oil,
dimensionless; $B_w$ - formation water volume coefficient, dimensionless; $W_r$ - reservoir cumulative water injection, $10^4$m$^3$; $W'_r$ - reservoir cumulative water production, $10^4$m$^3$; $p_i$ - original formation pressure, Mpa; $p$ - current formation pressure, Mpa; $\rho$ - ground degassing crude oil density, dimensionless; $\Delta p$ - reservoir pressure drop, Mpa; $\Delta p_w$ - oil well production pressure drop, Mpa; $C_{eff}$ - reservoir effective compression coefficient, Mpa$^{-1}$; $A$ - single well control oil area, km$^2$; $h$ - effective thickness of oil layer, m; $\phi$ - porosity, dimensionless; $S_w$ - water saturation, dimensionless; $q$ - average daily oil production, t/d; $t$ - oil well production time, day.

3.2. The reasonable water injection timing calculation of material balance method

The reasonable water injection timing is obtained when the bottom hole flowing pressure drops to the saturation pressure. According to the actual geologic conditions of C30 fault block, the effective thickness of oil layer is 10m and the initial average single well output is 10t/d. The C30 fault block development is carried out by adopting triangle well network with 300m well distance at the beginning. And the average production pressure drop is 3.0MPa. As can be seen from figure 3, the reasonable water injection timing is 3.2 months by using material balance method.

![Figure 3. The relationship between well output and reasonable water injection timing](image)

It can be seen from calculation results of material balance method, the relationship between the oil well output and the reasonable water injection timing of C30 fault block in different well control radius is obtained. The greater well control radius and lower well output lead to more time of the bottom hole flowing pressure reaching the saturation pressure.

4. The Verification of calculation result accuracy

It can be seen from the calculation results, the calculation results of the bounded layer quasi-steady state well test method and the material balance method are similar. According to the actual geologic conditions of C30 fault block, the initial average single well output is 10t/d and the drainage area radius is 150m. The calculating reasonable water injection timing is 3.3 and 3.2 months respectively by two methods. In order to further verify the reliability of the calculation results, the actual reservoir production situation is used to verify the method.

The C30 fault block is developed by natural energy in early stage of development, because the high saturation reservoir has abundant natural energy. The initial oil well output is higher, and the gas-oil ratio of the first three months rises continuously. The analysis is only the wellbore and immediate vicinity of wellbore degassing. The gas-oil ratio of 4-6 months is steady, the analysis is the initial
reservoir degassing. After a slight drop of gas-oil ratio, the gas-oil ratio of 7-9 months rises rapidly. After large scale degassing and oil well output declining sharply, water flooding measure is taken to develop the oilfield. The gas-oil ratio decreases and the oil well output increases due to effective response of water flooding. Therefore, the reasonable water injection timing is about three months after the oil well open up in order to prevent reservoir degassing. The results of the quasi-steady state well test method and the material balance method are similar, which shows that the calculation results of the two methods are reliable.

5. Conclusion
(1) The characteristics of complex fault block high saturation reservoir are the scattered oil sand body development and small oil drainage area. In view of these characteristics, the reasonable water injection timing of the reservoir is obtained by using the quasi-steady state well test method of finite layer and the material balance method. The results of the two methods are reliable according to the result of calculation compared with the actual production situation.

(2) As can be seen from the calculation results and actual production situation of C30 fault block, the time of bottom hole flowing pressure reaching saturation pressure is short, which is only three months. Therefore, considering the reservoir degassing and pressure wave transmission lag, water flooding should be taken early in the process of high saturation reservoir development.

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