Research Article

Research on the Water Production Tracking Method of Horizontal Well in Heavy Oil Reservoir with Bottom Water

Pan Yue,1,2 Wang Kai,1,2 Tang Chenyang,1,2 Li Ke,1,2 and Liu He3

1CNOOC Research Institute Ltd., Beijing 100028, China
2State Key Laboratory of Offshore Oil Exploitation, Beijing 100028, China
3CNPC Bohai Drilling Engineering Company Limited, Tianjin 300450, China

Correspondence should be addressed to Wang Kai; wangkaiupc@163.com

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At present, the model of heterogeneous fluid production in horizontal wells in bottom water reservoirs does not comprehensively consider the influence of parameters such as flow, length, and position of each production section, resulting in the distortion of interpretation results. Using the Green function and the Newman product method, this paper derives heterogeneous fluid production in horizontal wells in the bottom water heavy oil reservoir. The Stehfest numerical inversion algorithm was used to obtain the bottom fluid pressure solution of the horizontal well production in the bottom water heavy oil reservoir with the wellbore storage effect and skin effect. By drawing the typical chart of horizontal well test in sections, the new model can be divided into five typical flow stages: wellbore storage stage, transition stage, radial flow stage, linear flow stage, and late stable flow stage. Based on the interpretation of conventional parameters, such as permeability, well storage, and skin effect, the new model can further diagnose the parameters such as liquid production length, liquid production position, and liquid production volume of each horizontal section. The field application examples verify the validity of the research results and broad application prospects.

1. Introduction

The development of heavy oil reservoirs with bottom water is one of the big challenges in the oil and gas exploitation field worldwide [1, 2]. Developing reservoirs in these types, it often shows early water appearance, short water-free period, high water-cut ratio, and even violent water-cut ratio after water breakthrough, which reduces oil recovery and increases oilfield production risk [3, 4].

Currently, the application of horizontal well has been widely known as an effective technology to enhance oil recovery for heavy oil reservoirs with bottom water, especially for those with thin layers [5, 6]. Compared with vertical well, horizontal well has the advantages of larger contact area with the reservoir and smaller production pressure drop, which results in larger water cone, higher sweeping efficiency, lower drawdown, higher improved oil recovery, and better economics.

However, with the continuous development of oilfields, bottom water is likely to invade horizontal wells, resulting in a rapid rise in water cut and even water flooding, resulting in a decline in oil production and even shutting in [7–9]. Therefore, clarifying the flooding law of horizontal wells in heavy oil reservoirs with bottom water and accurately predicting the water outlet position of horizontal wells are of great significance for judging whether horizontal wells need water shutoff measures and how to take water shutoff measures [10, 11].

In terms of predicting the location of flooding and water outlet, the current process methods are mainly mechanical and chemical methods of finding water [12–14]. However, this method has the disadvantages of high test cost, immature technology, and certain construction risks. At present, there are still a few wells implementing this technology. The dynamic method and the numerical simulation method generally rely on the water cut change or the second derivative curve.
change of the water cut and the development index to determine the flooding law or the water outlet position of the horizontal well [15–17], but there are still data when calculating with actual data problems such as many noises, low operability, and high peak overlap interference.

Different from the conventional well test model, the new model can further diagnose the liquid production length, liquid production location, liquid production volume, and other parameters of each horizontal section (heel, middle, and toe) on the basis of interpreting the conventional parameters (permeability, well storage, and skin), which helps to further judge the water outlet position and implement reasonable water blocking or control measures.

2. Model and Method Section

2.1. Physical Model. A physical model of nonuniform fluid production from horizontal wells in bottom water reservoirs is established [18, 19]. As shown in Figure 1, the top of the model is the impermeable boundary, and the bottom is the bottom water boundary. There is a horizontal well in the horizontally infinite reservoir [20–23]. The wellbore of the horizontal well is parallel to the $x$-axis, and the length is $L$. There are $N$ production sections on the wellbore and are separated by nonproduction sections. The length of the $i$th production section is $L_{wi}$, the output is $q_{wi}$, the skin coefficient is $S_{wi}$, and the center is at $(x_{wi}, y_{wi}, z_{wi})$. The reservoir is homogeneous and anisotropic: the horizontal permeability is $k_\parallel = k_\perp = k_h$, and the vertical permeability is $k_v$. The formation porosity is $\phi$, the original formation pressure is $p_r$, the comprehensive compressibility is $C_t$, and the fluid viscosity is $\mu$. Only single-phase fluids are considered, and the effects of capillary force and gravity are not considered.

2.2. Mathematical Model. Initial conditions:

$$p(t = 0) = p_i.$$  

(1)

Inner boundary conditions:

$$\left( \frac{\partial p}{\partial r} \right)_{r=r_{wi}} = \frac{q_i \mu B}{2\pi k_h}.$$  

(2)

Outer boundary conditions:

$$p(r \rightarrow \infty) = p_i.$$  

(3)

Considering the permeability anisotropy, for the three-dimensional seepage problem of horizontal wells, the following formula is introduced:

$$z^* = z \sqrt{\frac{k_\parallel}{k_v}}.$$  

(4)

Therefore, the three-dimensional partial differential equation of horizontal well seepage can be reduced to the following standard form:

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{\eta} \frac{\partial p}{\partial t},$$  

(5)

$$\eta_h = \frac{k_h}{\phi \mu C_t},$$  

(6)

$$\eta_v = \frac{k_v}{k_p} \eta_h = \beta^2 \eta_h.$$  

(7)

In this formula, $x$, $y$, and $z$ are the coordinates of any point in the reservoir; $z^*$ is the coordinate in the $z$ direction considering anisotropy; the pressure conduction coefficient in the horizontal well direction is $\eta_h$; the pressure conduction coefficient in the vertical direction is $\eta_v$.

According to the instantaneous source solution and the Newman product method, the formation pressure distribution formula of the $i$th production section in the model is obtained as follows:

$$\Delta p(x, y, z, t) = p_i - p(x, y, z, t) = \frac{1}{\phi \mu C_t} \int_0^t G_x G_y d\tau.$$  

(8)

Among them,

$$G_x = \frac{1}{2} \left\{ \text{erf} \left[ \frac{L_{wi}/2 + (x - x_{wi})}{\sqrt{4\eta_h \tau}} \right] + \text{erf} \left[ \frac{L_{wi}/2 - (x - x_{wi})}{\sqrt{4\eta_h \tau}} \right] \right\},$$

$$G_y = \frac{1}{\sqrt{4\pi \eta_h \tau}} \exp \left[ -\frac{(y - y_{wi})^2}{4\eta_h \tau} \right] \cdot \frac{2}{h^2} \sum_{n=1}^{\infty} \left\{ \sum_{n=1}^{\infty} \exp \left[ -\frac{(2n - 1)^2 \pi^2 \eta_v \tau}{4h^2} \right] \cdot \cos \left[ \frac{(2n - 1)\pi z_{wi}}{2h} \right] \right\},$$

$$h^* = h \sqrt{\frac{k_\parallel}{k_v}}.$$  

(9)
In this formula, \( h \) is the thickness of the oil layer; \( h^* \) is the equivalent thickness of the oil layer considering anisotropy.

Define the following dimensionless quantities:

\[
P_D = \frac{2\pi k_h h^* [p_i - p(x, y, z, t)]}{q \mu},
\]

\[
t_D = \frac{k_h t}{\phi \mu C_G L^2} = \eta_h \frac{t}{L^2},
\]

\[
h_D^* = \frac{h^*}{L},
\]

\[
r_{wd} = \frac{r_w}{L},
\]

\[
x_D = \frac{x}{L},
\]

\[
y_D = \frac{y}{L},
\]

\[
z_D = \frac{z}{L},
\]

\[
x_{wd} = \frac{x_{wd}}{L},
\]

\[
y_{wd} = \frac{y_{wd}}{L},
\]

\[
z_{wd} = \frac{z_{wd}}{L},
\]

\[
L_{wd} = \frac{L_{wd}}{L},
\]

\[
L_{Di} = \frac{L_{Di}}{R^*},
\]

\[
C_D = \frac{C}{2\pi h^* \phi C_G L^2},
\]

\[
q_{wd} = \frac{q_{wd}}{\sum_{i=1}^{N} q_{wi}}.
\]

Substituting the definition formula of the dimensionless quantity into formula (5), we can get

\[
P_D(x_D, y_D, z_D, t_D) = \sum_{i=1}^{N} \sqrt{\pi} \frac{q_{wd} t_D}{L_{wd}} G_{\Delta D} G_{yzD} d\tau_D.
\]

Among them,

\[
G_{\Delta D} = \text{erf} \left( \frac{L_{wd}/2}{4 \sqrt{t_D}} \right) + \left( x_D - x_{wd} \right) \frac{q_{wd}}{L_{Di}} S_{wi},
\]

\[
G_{yzD} = \frac{1}{\sqrt{t_D}} \exp \left[ - \left( \frac{y_D - y_{yzD}}{4 t_D} \right)^2 \right].
\]

Taking into account that each production section has a different skin coefficient \( S_{wi} \), using the principle of superposition, the formation pressure distribution at the bottom of the nondimensional horizontal well under the action of \( N \) production sections can be obtained.

\[
P_{SD}(x_D, y_D, z_D, t_D) = \sum_{i=1}^{N} \sqrt{\pi} \frac{q_{wd} t_D}{L_{wd}} G_{\Delta D} G_{yzD} d\tau_D + \frac{q_{wd}}{L_{Di}} S_{wi}.
\]

Consider the impact of wellbore storage effect:

\[
P_{wd}(C_D, u) = \int_{0}^{t_D} \left[ 1 - C_D \frac{dp_{wd}}{dt_D} \right] \frac{dp_{wd} (t - \tau)}{d\tau} d\tau.
\]
horizontal wells in Laplace space can be obtained considering skin effect and well storage effect.

\[ P_{wD}(C_{D}, S, u) = \frac{\tilde{P}_{SD}(u)}{1 + u^2 C_{DP}_{SD}(u)}. \]  \hspace{1cm} (15)

In the formula, \( P_{SD} \) is the solution in the pull space when the well storage effect is not considered but the skin effect of each production section is considered, and \( u \) is the pull variable. According to the result of formula derivation, a well test analysis module can be compiled, and the well test analysis module can be used to form a typical curve and a typical chart of the horizontal well segmented water production pattern, which provides technical support for horizontal wells in bottom water reservoirs.

3. Results and Discussion

3.1. Model Verification. Comparing the nonuniform fluid production model of the horizontal well with the entire fluid production model, it can be observed that the typical curves

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at different flow stages are obviously different [24, 25]. The nonuniform fluid production model of horizontal wells in bottom water reservoirs has one more linear flow stage than the entire fluid production model, as shown in Figure 2. Therefore, the model can be used to determine the effective production section length of horizontal wells in bottom water reservoirs and diagnose the location of high-production fluids, thereby providing a reliable basis for formulating water control measures.

3.2. Sensitivity Analysis of Plate Parameters

3.2.1. Production Section. The number of production sections \( N \) is 2, 3, and 4, respectively. The total length of the
horizontal well is \( L \), the total length of the effective output sections is \( 0.375L \), the total flow rate is \( q \), and the length, flow, skin coefficient, and other parameters of each production section are uniformly distributed. Thus, typical well test curves of nonuniform liquid production of horizontal wells in bottom water reservoirs with different production sections \( N \) were obtained, as shown in Figure 3. While keeping the total length of the effective output sections constant, the more production sections, the smaller the effect on the pressure response of the heel of the horizontal well, and the smaller the pressure drop in the radial flow stage.

3.2.2. Dimensionless Distance. The dimensionless distance is defined as the ratio of the distance between the midpoints of two adjacent production sections to the total length of the horizontal well [26]. Assuming that there are two production sections in a horizontal well, one production section is fixed at the heel of the horizontal well, and the dimensionless distance \( \Delta xD \) is, respectively, 0.2, 0.4, 0.6, and 0.8. The length and skin coefficient of the two production sections are all equal. Thus, typical well test curves of nonuniform liquid production of horizontal wells in bottom water reservoirs with different dimensionless distances \( \Delta xD \) were obtained, as shown in Figure 4. The well storage stage and the transition flow stage are not affected by the dimensionless distance, while the pressure drop in the radial flow and linear flow stages decreases with the increase of the dimensionless distance.

3.2.3. Segmented Flow Rate (Liquid Production in Partial Horizontal Sections). The total length of the horizontal well is \( L \), the total length of the effective oil production section is \( 0.375L \), and the number of production sections is 3. Keep the total flow constant at \( q \), the length of each production section, skin coefficient, etc., are uniformly distributed, and the flow \( q_{\text{sub}} \) is unevenly distributed. Thus, typical well test curves of the fluid production in partial horizontal section of a horizontal well in a bottom water reservoir with a nonuniform flow rate distribution are obtained, as shown in Figure 5.

Overall, each flow stage is affected by the flow distribution. The five situations in Figure 6 can be divided into three categories: the three sections of flow are not equal; the flow rates of the heel production section and the toe section are equal; the three sections are all equal. Analyzing the three types of flow rate distributions can get the following conclusions: when the heel flow rate is large, the pressure drop is large; when the heel flow rate is small, the pressure drop is small. Meanwhile, it can be observed that when the flow rates of the heel production section and the toe section are equal, the pressure derivative curves of the steady flow coincide at the late stage. When the flow distribution of each production section is different, there are obvious characteristics in pressure and pressure derivative. Therefore, the model can be used to identify the high-yield section, so as to provide a theoretical basis for the formulation of the next plugging measures.

3.2.4. Segment Flow Rate (Liquid Production in All Horizontal Sections). The total length of the horizontal well is \( L \), the horizontal well produces fluids in all sections, and the number of production sections is 3. Keep the total flow
constant at \( q \), the length of each production section, skin coefficient, etc., are uniformly distributed, and the flow \( q_{\text{wiD}} \) is unevenly distributed. Thus, typical well test curves with fluid production in all horizontal sections of horizontal wells in a bottom water reservoir with nonuniform flow distribution are obtained, as shown in Figure 5. Each flow stage is affected by the flow distribution of each production section, as follows:

In general, the flow rate at the heel of the horizontal well has the greatest effect on the pressure response. The greater the flow in the heel production section, the greater the overall pressure drop in each flow stage. When the flow in the production section of the heel remains constant, the flow distribution in the middle and toe of the horizontal well does not affect the pressure drop in the well storage stage, transition stage, and radial flow stage. At this time, the greater the flow in the middle production section, the greater the pressure drop during the transition from radial flow to late steady flow. The more uniform the flow distribution in each section, the more uniform the bottom water will advance upward. The later the ridge advance occurs, the later the steady flow occurs. It can be observed from Figure 7 that when the flow rates in all sections are equal, the late stable flow appears the latest. When the flow rates in the heel and toe production sections of a horizontal well are equal, the late stable flow pressure derivative curves coincide. When the flow distribution of each production section is different, there are obvious characteristics in pressure and pressure derivative, so the model can be used to identify the high-yield liquid section, so as to provide a theoretical basis for the formulation of the next plugging measures.

3.2.5. Degree of Anisotropy. The total length of the horizontal well is \( L \). It is assumed that there is a production section at the heel and toe of the horizontal well. The lengths of the two production sections are both 0.2 \( L \), and the skin coefficient and other parameters are equal. Keep the horizontal permeability constant at 1D, and change the degree of anisotropy by changing the longitudinal permeability. Thus, typical well test curves of nonuniform fluid production of horizontal wells in bottom water reservoirs under different degrees of anisotropy are obtained, as shown in Figure 7.

The greater the ratio of longitudinal permeability to horizontal permeability, the faster the bottom water advances upward, the earlier the horizontal well can receive energy from the bottom water, the earlier it reaches the late stable flow stage, and the earlier the pressure derivative curve falls. As the longitudinal permeability increases, the linear flow will gradually disappear. At this time, the characteristics of the nonuniform fluid production model on the derivative

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**Table 1: The conventional bottom water model test interpretation results.**

| Well length (m) | Wellbore storage effect (m³/MPa) | Formation coefficient (mD·m) | Permeability (mD) | Skin effect (-) | Original formation pressure (MPa) | Water avoidance height (m) |
|-----------------|----------------------------------|------------------------------|------------------|----------------|-------------------------------|--------------------------|
| 395             | 2.9                              | 4687                         | 586              | 0              | 13.25                         | 7                        |

**Table 2: Heterogeneous fluid production bottom water model test interpretation results.**

| Well length (m) | Wellbore storage effect (m³/MPa) | Formation coefficient (mD·m) | Permeability (mD) | Skin effect (-) | Water avoidance height (m) | Position (m) |
|-----------------|----------------------------------|------------------------------|------------------|----------------|----------------------------|---------------|
| 420             | 2.3                              | 4300.8                       | 537.6            | -1.0           | 7                          | 65            |
| Production section 1 (heel) | Length (m) 130 | Liquid volume (m³) 320 | Position (m) 200 | Production section 2 (toe) | Length (m) 80 | Liquid volume (m³) 40 | Position (m) 300 | Production section 3 (middle) | Length (m) 110 | Liquid volume (m³) 160 |

**Figure 11: Heterogeneous fluid production bottom water model.**
curve are masked, which is not conducive to the diagnosis of the high fluid production section.

3.2.6. Skin Coefficient. The total length of the horizontal well is \( L \), the total length of the effective production section is \( 0.3L \), and the number of production sections is 3. When the length, flow rate, skin coefficient, and other parameters of each production section are uniformly distributed, as shown in Figure 8(a), the larger the total skin coefficient, the later the hump appears and the higher the peak value. When the sum of the skin coefficients of each section remains unchanged, since the total skin effect is the result of the combined effect of the length, flow rate, and skin coefficient of each production section, if the length and flow rate of each production section are equal, the unevenly distributed skin does not affect the pressure response. If the length and flow of each production section are different, the non-uniform distribution of the skin coefficient of each production section will have a certain impact on the pressure and derivative curve. The production section with a large flow will play a leading role on the total skin, but the effect is not obvious, as shown in Figure 8(b). Therefore, the skin coefficient cannot play a key role in the diagnosis of the high-yield section.

4. Example Application

Well A is located in production layer with an average effective thickness of 16.8 m. The effective horizontal length of Well A is 432 m. The water cut of Well A rises rapidly, as shown in Figure 9.

The conventional bottom water model is used for well test interpretation (Figure 10), and the interpretation results are shown in Table 1.

A heterogeneous fluid production bottom water model is used for well test interpretation (Figure 11), and the interpretation results are shown in Table 2.

The results showed that the heel and toe were high-yield liquid positions, and the middle contributed less yield.

5. Conclusion

A method for predicting the water output position of horizontal wells in heavy oil reservoirs with bottom water is constructed, and based on the new method, five typical flow stages are divided: wellbore storage stage, transition stage, radial flow stage, linear flow stage, and late steady flow stage. Based on the new method, a plate of the influence law was formed, which concerns factors such as the flow of each horizontal section, the degree of anisotropy, and the skin coefficient. The example application of this method is in good agreement with the actual test results, and it can provide a theoretical basis for the prediction of the water outlet position and water shutoff operation of a horizontal well in a bottom water heavy oil reservoir, and it has a good prospect.

Data Availability

Data will be available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Pan Yue and Wang Kai contributed equally to this work.

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