The Residual Potential of Bottom Water Reservoir Based upon Genetic Algorithm for the Relative Permeability Inversion

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Abstract

X oilfield has successfully adopted horizontal wells to develop strong bottom water reservoirs, as a typical representative of development styles in the Bohai offshore oilfield. At present, many contributions to methods of inverting relative permeability curve and forecasting residual recoverable reserves had been made by investigators, but rarely involved in horizontal wells’ in bottom water reservoirs. As the pore volume injected was less (usually under 30 PV), the relative permeability curve endpoint had become a serious distortion. That caused a certain deviation in forecasting residual recoverable reserves in the practical value of field directly. For the performance of water cresting, the common method existed some problems, such as no pertinence, ineffectiveness and less affecting factors considered. This paper adopts the streamlines theory with two phases flowing to solve that. Meanwhile, based on the research coupling genetic algorithm, optimized relative permeability curve was calculated by bottom-water drive model. The residual oil saturation calculated was lower than the initial’s, and the hydrophilic property was more reinforced, due to improving the pore volume injected vastly. Also, the study finally helped us enhance residual recoverable reserves degree at high water cut stage, more than 20%, taking Guantao sandstone as an example. As oil field being gradually entering high water cut stage, this method had a great significance to evaluate the development effect and guide the potential of the reservoir.

Keywords

Bottom Water Reservoir, Horizontal Well, Water Cut, Genetic Algorithm, Residual Potential
1. Introduction

The oil-water relative permeability curve was an indispensable and important data in oilfield development, representing the seepage characteristics of oil and water phases in porous media.

Usually in the bottom water reservoir, the swept volume of horizontal Wells was difficult to expand at the extremely high water cut stage, Permadi & Jayadi (2010). However, a large number of data show that with the increase of pore volume injection multiple, the oil displacement efficiency in the swept area could be further improved Gao, Jiang, Wang, et al. (2016) and Wang & Zhao (2012). The conventional relative permeability curve endpoint value couldn’t reflect the actual production of the bottom water reservoir Zheng, Xu, & Chen (2013), due to large differences of residual oil saturation acquired by laboratory test and actual condition. The mainstream line area was actually displaced by thousands of pore volume, more than 30 PV under the experimental conditions. Conventional inversion method of relative permeability curve was calculated by the water-oil phase flow theory Zheng (1993), and Liu (1996), but the process hasn’t taken factors into account such as reservoir types, the development way, the well type, etc. Also, the uncertainty endpoint value data of permeability curve was improperly considered as the known parameters, resulting in a certain deviation put into field application with conventional methods, Chen & Tao (1997), Bing (2012), and Yang, Zhou, Qiu, et al. (2010).

Therefore, the conventional method had been unable to accurately invert the morphological parameters and endpoint values of the permeability curve for the bottom water reservoir. In view of the above problems, a numerical inversion method of permeability curve was proposed based on genetic algorithm for bottom water reservoir.

2. The Method for Analysis of the Residual Potential of Bottom Water Reservoir

2.1. Establishment of Theoretical Model for Bottom Water Reservoir

Taking Bohai X oilfield adopted horizontal well development with strong bottom water as an example, compared with conventional development oilfield by water injection, water crest was dominant in the vertical direction, with rapid water cut, large decline rate initially, and long duration of high water cut stage. Based on the analysis of actual reservoir displacement process and the rule of oil-water two-phase percolation, the model of homogeneous bottom-water flooding considering anisotropy was established. The hypothesis is: 1) the reservoir was homogeneous and anisotropic; 2) ignore the influence of capillary force and gravity; 3) the bottom water energy is sufficient, the original oil-water interface at the bottom is the constant pressure boundary; 4) reservoir rock and fluid was incompressibility; 5) steady flowing.

As shown in Figure 1, the swept volume tended to be stable at extremely high
water cut stage for the horizontal well of bottom water reservoir. In view of the profile of water crest, the relationship between the radius of water crest and the height of water cone was usually obtained by mathematical fitting methods, Xin (2011), as shown in Formula (1).

\[ h(r) = a_1 + a_2 e^{-ar^2} \]  

(1)

In the formula, \( r \), sweep radius of transverse sweep region, m; \( h \), the height of vertical water ridge, m; \( a_1, a_2 \), constants, related to crude oil viscosity, horizontal and vertical permeability ratio, reservoir thickness, water-repellent height, liquid production level and other factors.

The stream tube model assumed that the fluid flow in the porous medium was stable and streamlines remained unchanged during the displacing process. Therefore, according to Equation (1), the distribution of different streamlines in the swept area of horizontal well in bottom water reservoir could be determined, and then the simulated regionalization could be divided into multiple flow pipes. In order to reduce the error and facilitate the simulation calculation, each flow pipe adopted the method of mesh subdivision, and the subdivision results were shown in Figure 2.

The oil-water flow in the stream tube model satisfied the B-L equation, Sun, Zhou, Hu, et al. (2018), and the flow equation in the coordinate system was,

\[ \left( \frac{d\xi}{dt} \right)_{S_w} = \frac{Q(t)}{\phi(\xi)A(\xi)} \left( \frac{\partial f_w}{\partial S_w} \right)_{S_w} \]  

(2)

In the formula, \( \xi \), the position at a certain water saturation of time \( t \) in the model; \( \left( \frac{\partial f_w}{\partial S_w} \right)_{S_w} \), the derivative of fractional flow equation at \( S_w \); \( \phi \), porosity; \( A \), the cross-sectional area of the seepage, m\(^2\); \( Q(t) \), cumulative flowing volume from the injection side, m\(^3\).

According to the differential form of saturation-of-frontal-advance Equation (2), the frontal-advance saturation position and change law at a certain time could be calculated by the model.

\[ x - x_o = \frac{f'_w(S_w)}{\phi A} \int_0^t q dt \]  

(3)

Figure 1. Swept volume sketch map of horizontal well in bottom-water reservoir.
Figure 2. Mesh generation of water coning in bottom-water reservoir.

Darcy formula was introduced to calculate the relative permeability value, under the saturation distribution in each flow tube. The flow rate of each flow tube at a certain moment was calculated according to the law of equivalent percolation resistance, Sun, Zhou, Hu, et al. (2018).

\[ q = \frac{\Delta P}{R} \]  

In the formula, \( \Delta P \), production differential pressure in flow pipe, MPa; \( R \), seepage resistance, and the calculation formula is

\[ R = \sum_{i=1}^{N} \frac{L_i}{A_i \cdot (\lambda_{oi} + \lambda_{wi})} \]  

In the formula, \( A_i \), the seepage area of the flow pipe at a grid I, m²; \( L_i \), the length of the flow pipe division at a grid I, m; \( \lambda_{oi} \), \( \lambda_{wi} \), the mobility of oil phase and water phase at a grid I; \( N \), the number of longitudinal meshes of the flow tube.

Through the above formula, the relationship between the flow rate and time in each flow pipe could be established. At the same time, the development index of the affected area could be obtained by superimposing the results of each flow pipe.

2.2. Genetic Algorithm Coupled with Bottom Water Flooding Theory Model

The permeability curve was generally expressed in exponential form:

\[ k_{rw} = k_{rw,0} \cdot S_{ow}^{S_{ow}^*} \quad ; \quad k_{rw} = k_{rw,0} \cdot (1 - S_{ow})^{S_{ow}^*} \]  

In the formula, \( k_{rw,0} \), \( S_{ow,0} \), the initial maximum oil relative permeability with the value 1.0 after normalization; \( S_{ow}^* = \frac{S_{ow} - S_{wi}}{1 - S_{wi}} \), \( S_{ow} \) water saturation; \( S_{wi} \) irreducible water saturation; \( S_{ow} \) residual oil saturation.
In the Formula (3), the initial water saturation could be measured by closed coring, mercury intrusion, logging and other methods, Yan, Li, Yin, et al. (2009). As shown in Figure 3, the parameters of permeability curve were analyzed as uncertain, including $C_w$, $C_o$ and the endpoint values of $S_{or}$ and $K_{rw-Sor}$. In order to solve the above problems, the four uncertain parameters of the permeability curve could be determined by indirect means through the established theoretical model, by using a large number of dynamic data of production wells in bottom water reservoir.

Genetic algorithm (GA) is a computational model simulating natural selection and genetic mechanism of Darwinian evolution, Liang, Zhao, Song, et al. (2005). As shown in Figure 4, in this paper, the genetic algorithm was coupled with the bottom water drive model. Different characteristic parameters of relative permeability curve were generated through initial population, and theoretical curves were calculated by the theoretical model between water cut and recovery degree. The optimal solution with minimum of forecast error was determined compared with the actual production data.

![Figure 3. Parameter analysis of relative permeability curve.](image1)

![Figure 4. Flow chart of the research coupling genetic algorithm and bottom-water drive model.](image2)
3. The Analysis for Inversion Results of Permeability Curve

3.1. The Results of Calculating with the Bottom Water Drive Model

Taking the relative permeability curve of N1g III sand body (Figure 4) and the production data of A2H in Bohai X oilfield as examples, the well A2H was put into operation in 2005, and entered the ultra-high water cut stage after three years. The water cut changed steadily in the following 10 years. At present, the cumulative oil production is $32.06 \times 10^4$ m$^3$, the cumulative oil production proportion is 56% in the ultra-high water cut stage, and it is the main contributing stage of cumulative oil production. At present, the water cut of the well A2H is 97.0%, and the daily oil production is 37 m$^3$/d.

The results of water cut and recovery degree calculated by two different methods are shown in Figure 5. According to the diagram, it could be seen that there was a big difference between the calculation results of conventional phase permeability curve combined with fractional flow equation and the actual production performance data. The reason was that the conventional method could not accurately describe the water ridge law and production performance characteristics, due to not considering the factors of reservoir type, development mode and well type. The calculation results of theoretical model of bottom water drive coincided with the actual production performance data to some extent, but in the later stage, the water cut rised rapidly and the fitting effect was poor. The reason was that the main displacement path scour multiple was more than 1000 times in the ultra-high water cut stage of the bottom water reservoir. A lot of studies showed that the displacement efficiency was still increasing at this stage, Chen, Bai, Lv, et al. (2015), and Yan & Jiao (2014), and Yin, Zhao, Dong, et al. (2012), so the residual oil saturation measured by conventional phase permeability curve could not accurately describe the development law of the ultra-high water cut stage of the bottom water reservoir.
3.2. Calculation Results of Genetic Algorithm Coupled with Theoretical Model of Bottom Aquifer Drive

After optimizing the theoretical model of bottom aquifer drive by coupling genetic algorithm, the results were shown in Figure 6. From the graph, it could be seen that the optimized calculation results of this method were in good agreement with the actual dynamic data, and it could accurately describe the characteristics of water cut change slowing down during the ultra-high water cut period of bottom water reservoir.

3.3. Analysis of Optimized Relative Permeability Curve

The relative permeability curves measured by laboratory experiments generally reflected the reservoir characteristics of horizontal plane flow, while the bottom water reservoir was a vertical displacement process from bottom to top, due to the sedimentation of reservoir rocks, the seepage characteristics of horizontal and vertical water flooding were different, so the corresponding phase permeability curves would be quite different. As shown in Figure 7, the residual oil saturation of the optimized relative permeability curve was 0.1, which was lower than the original oil saturation. This showed that the displacement efficiency of the swept area could be greatly improved by relying on the high PV scouring multiple in the ultra-high water cut stage of the bottom water reservoir. The optimized relative permeability curve reflected the hydrophilic property of the reservoir, in the area swept by the bottom water in the ultra-high water cut stage, so the iso-permeability point moved to the right and reservoir hydrophilicity was stronger after high scouring multiple. By comparing the water cut of the relative permeability curve with the displacement efficiency curve, it could be seen that the water cut change of the optimized relative permeability curve was basically the same as that of the original relative permeability curve in the middle and low water cut stage, while in the ultra-high water cut stage, the water cut change of the optimized relative permeability curve was relatively slow, which was more in line with the actual production performance of the oilfield.

Figure 6. Calculation result of optimized relative permeability curve based on genetic algorithm.
3.4. Digital Verification and Its Application

The optimized relative permeability curve was brought into the numerical simulation calculation, and the fitting of A2H well in N1g III sand body was shown in Figure 8. Fitted by the original phase permeability curve, the water content curve was higher than the actual data of A2H well, and the optimized relative permeability curve fitting results were more in line with the actual water cut change law of the well.

The original relative permeability curve predicted water cut to 98% by the end of 2015. Due to the high water cut calculation, the technical recoverable reserves prediction was only 281,800 m³, which was less than the current actual cumulative oil production of 316,800 m³, which contradicted the actual production data. The relative phase permeability curve predicted water cut to 98% by 2020, when the production time would reach 381,400 m³. Compared with the numerical simulation results of the original relative permeability curve, the predicted recoverable reserves of technology increased by 100,000 m³. Therefore, through this method, the dynamic data of ultra-high water cut reservoir could be accurately fitted, and the residual potential of old wells in ultra-high water cut reservoir could be further recognized. This study could provide a theoretical basis for dynamic prediction and fine tapping of potential of old well pattern in ultra-high water cut reservoir.

4. Conclusion

1) Combining with the oil-water two-phase seepage law of horizontal wells in bottom water reservoirs, a theoretical model of bottom-water flooding horizontal wells based on flow tube method was established.

2) The optimized calculation results were in good agreement with the actual data of N1g III sand, and it could accurately describe the characteristics of water cut change slowing down during the ultra-high water cut period of bottom water reservoir.

3) Compared with the numerical simulation results of the original relative permeability curve, the dynamic data of ultra-high water cut reservoir could be accurately fitted by the optimized relative permeability curve.
Figure 8. The curves of numerical calculation based on optimized relative permeability curve.

In this paper, coupled with the horizontal well model of bottom water driven by genetic algorithm, the numerical inversion of the relative permeability curve of heavy oil reservoir with bottom water was realized, and the phase permeability curve conforming to the actual production of oil field was obtained by optimizing the solution. Good results were obtained in the application of mathematical model, which could provide some guidance for dynamic prediction and fine tapping potential of bottom water reservoir in ultra-high water cut period.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References


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