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Numerical Simulation Study and Application of C Oilfield during the Ultra-High Water Cut Stage Considering Time-Varying Relative Permeability

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Abstract

To accurately study the distribution pattern of remaining oil during the ultra-high water cut stage of C Oilfield, 16 sets of 2000 PV waterflooding experiments were conducted. Based on the experimental results, a regression analysis was performed to obtain the variation pattern of oil displacement efficiency. Combined with the correlation results between irreducible water saturation and reservoir physical properties in well logging experiments, a quantitative expression for residual oil saturation considering physical properties, crude oil viscosity, and displacement PV was established. The dynamic characterization of residual oil saturation in numerical simulation was realized using the Python module in Petrel RE software. It was proposed to add the saturation of key sections of bypass wells as a historical fitting parameter, enabling iterative modification of residual oil saturation. The research results showed that the saturation of bypass wells considering time-varying relative permeability had a high degree of consistency with actual well logging interpretation results, and the fitting accuracy of numerical simulation was improved. This research achievement guides potential tapping and adjustment research during the high water cut stage of C Oilfield, laying a foundation for the subsequent formulation of planning schemes and potential tapping strategies for the oilfield.

Keywords

Ultra-High Water Cut Stage, Residual Oil Saturation, Time-Varying Relative Permeability, PV, Numerical Simulation

1. Foreword

As more and more oil fields enter the high water cut stage and ultra-high water cut stage, long-term waterflooding can cause changes in reservoir and fluid properties,

which essentially represents a long-term transformation of the subsurface (Sun et al., 2015). Long-term waterflooding improves reservoir physical properties, improves pore structure, and reduces shale content and irreducible water saturation (Li et al., 2001). Due to the injection water scouring effect, it causes the clay content in the pore to separate and drift, and results in cementation types translating pore-contact in the low and medium water cut period into pore type in the high water cut period (Tang et al., 2016). With the aggravation of reservoir water flooding, the reservoir physical parameters, pore structure parameters, and seepage characteristics have changed fundamentally (Yang et al., 2000). The most significant impact on development and remaining oil is the further improvement in oil displacement efficiency after long-term water flooding and the further reduction in residual oil saturation, which leads to a better understanding of the potential of the oilfield beyond the expectations of early development. Conventional reservoir numerical simulation software does not reflect the changes in reservoir parameters and percolation laws under high injection ratios. The variation characteristics of time-varying reservoir parameters and the modification of the numerical simulation model have been described from different perspectives (Lin, 2018). The mathematical model of the continuous change of the permeability and relative permeability curves with time is established, and the time-varying numerical simulation technology of physical properties suitable for medium and high permeability sandstone reservoirs is formed (Wang et al., 2019). A time-varying characterization method of physical properties based on surface flux is proposed, and the corresponding numerical simulation technology is established through field data analysis, black oil model improvement, and software programming (Zhang et al., 2015). The concept of effective cumulative water flux is proposed, and the critical velocity is used as the velocity limit for particles to begin migration, thus correcting the effect of water flux on reservoir permeability to a certain extent (Zhang, 2005).

Based on the analysis of experimental results, this paper establishes a quantitative mathematical equation to characterize residual oil saturation as a function of reservoir physical properties, fluid, and displacement ratio. By utilizing the Python module in Petrel RE software to write code for characterization and simulation calculations, the addition of dynamic residual oil saturation improves the historical fitting effect of the oilfield during the ultra-high water cut stage, achieving better matching with actual passing wells.

2. Experimental Research and Understanding of High-Multiple Displacement

2.1. Establish Experimental Scheme Design

Based on the physical properties of the strata and the range of underground crude oil viscosity in C Oilfield, a study was conducted on the law of high-fold displacement of water flooding under different physical properties (690 - 8669 mD) and different formation crude oil viscosity (50 - 600 mPa·s).

A high-multiple displacement experiment was carried out on 16 groups of cores; the test temperature is based on the formation temperature of 65˚C, and the test pressure is 11 MPa, consistent with reservoir conditions. The simulated oil viscosity ranged from 50 to 600 mPa·s; standard saline water displacement was employed, with a salinity of 10,000 mg/L and a displacement rate of 1.0 mL/min. The maximum displacement multiple was 2000 PV. The specific steps are as follows:

1) After washing, drying, and cooling the core, measure the length and radius of the core, and measure the permeability of the core;

2) Pump out saturated formation water, weigh the wet weight of the core, and calculate pore volume and porosity;

3) Place the core of 100% saturated formation water into the core holder, connect the process, and establish irreducible water saturation using the oil displacement method. Initially, use a low flow rate for oil displacement of water, gradually increasing the displacement speed until no water is discharged, and calculate the saturation of bound water;

4) Conduct a water flooding experiment at the speed designed in the experiment;

5) Accurately record the cumulative oil production and cumulative fluid production at the time of water breakthrough;

6) At the initial stage of water breakthrough, increase the frequency of recording, and select the time interval based on the amount of oil produced. As the oil production continues to decrease, gradually lengthen the recording time interval, and terminate the experiment when the water injection multiple reaches 2000 PV.

2.2. Analysis of Experimental Results

Compared with the oil displacement efficiency measured in the conventional waterflooding experiment with 30 PV displacement, as shown in Table 1, the oil displacement efficiency after 2000 PV waterflooding increased by 10.1% to 15.9%, with an average increase of 14.0%. The potential of the high-multiple displacement stage cannot be ignored.

A statistical analysis was conducted on the extent of oil displacement efficiency improvement across different displacement multiple intervals, as shown in Figure 1. From 30 PV to 200 PV, the oil displacement efficiency can be improved by an average of 10.8%. Further displacement from 200 PV to 1000 PV increases the oil displacement efficiency by 2.4%, while displacement from 1000 PV to 2000 PV only improves the oil displacement efficiency by 0.8%.

Significant changes occur in the pore size and distribution characteristics of rocks before and after waterflooding. Waterflooding alters the pore structure of the reservoir, reduces the content of cement in sandstone, increases the pore throat radius, and forms large seepage channels. At different stages of the waterflooding process, the degree of pore structure alteration in the reservoir varies, leading to different oil displacement capacities. The efficiency of waterflooding varies with the increase in waterflooding multiples.

Table 1. Experimental results of high-multiple displacement water flooding in C Oilfield.

Core	Permeability, mD	Porosity, %	Irreducible Water Saturation, %	Oil Viscosity, mPa·s	30 PV Displacement Efficiency, %	2000 PV Displacement Efficiency, %
1-007D	5665.1	34.7	19.8	400	64.6	79.3
1-016C	1659.6	37.6	26.7	600	64.7	76.8
2-018C	5011.3	33.9	21.4	200	58.2	73.5
2-018D	4170.2	33.5	23	400	67.9	81.9
2-018E	3752.3	36.1	26.9	600	63.9	79.5
2-013E	5405.8	35.7	23.9	200	60.7	74.8
2-021D	690.7	33.6	27.3	200	60.6	70.7
4-006J	7825.6	35.4	19.7	50	62.1	77.9
5-022D	6921.9	34.3	21.3	50	58.0	73.5
5-037D	932.7	29.4	29.3	50	59.3	71.5
5-040D	867.2	32.9	27.2	50	56.5	68.5
6-003D	4609.4	35	22.2	50	56.9	71.1
6-008D	3270.8	36	22.5	50	60.5	73.5
6-024E	5087.4	34.3	21.2	50	59.6	74.9
6-028E	8057.7	32.1	18.8	50	60.2	76.1
6-033D	9129	34.3	17.6	50	56.9	71.7

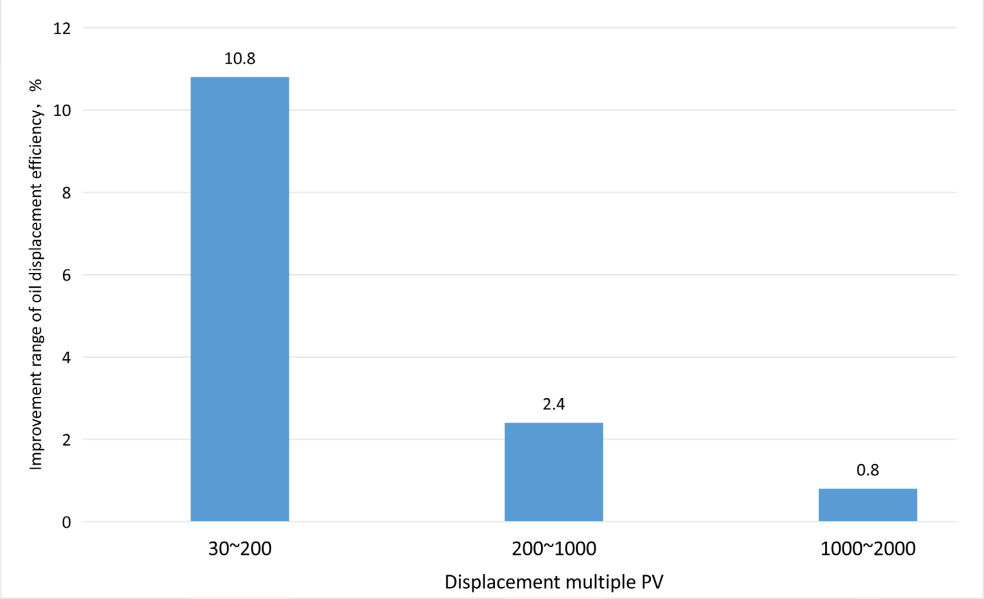


Figure 1. The increase in oil displacement efficiency under different displacement multiples.

The main factors affecting waterflooding efficiency are reservoir pore structure, fluid properties, and displacement conditions. When fluid properties and displacement conditions are constant, changes in pore structure inevitably lead to changes

in oil displacement efficiency. After long-term waterflooding scouring in the later stages of reservoir development, the pore structure characteristics may undergo significant changes due to the scouring and migration of mineral particles, detachment of clay films, etc., resulting in changes in physical properties and percolation capacity; the wettability becomes more hydrophilic.

Due to the weak cementation characteristics of the rock skeleton, the particles are easy to fall off and migrate with the fluid during the water injection process, resulting in a significant increase in pore heterogeneity. Long-term injection of water leads to cement dispersion; small particles fall off and migrate with the fluid. In areas with fine throats, these migrating particles are easy to accumulate and form blockages, which affects the connectivity of seepage channels and pore throat structure.

Before water flooding, polar substances are adsorbed on the rock surface, showing its oil-wetting property. With the progress of the water drive process, the polar sexual substances are washed away, weakening the wetting properties of oil. Rock surface oil molecules are gradually taken away by water under constant scouring, leading to desorption and the equilibrium of adsorption is destroyed. With the continuous scouring of the injected water, the balance shifts in the direction of desorption, so that the lipophilic surface of the porous medium gradually decreases.

In summary, oil displacement efficiency is not a constant value, but is comprehensively influenced by static parameters such as physical properties and fluid properties, as well as dynamic parameters such as displacement ratio.

3. Time-Varying Characterization of the End Points of Long-Term Waterflooding Relative Permeability

3.1. Residual Oil Saturation Variation Chart

The results indicate that as the displacement ratio increases, the residual oil saturation exhibits a decreasing trend. The impact of long-term waterflooding on residual oil saturation primarily manifests in changes to the mineral composition, pore throat structure, wettability, and other characteristics of the rock itself. With the increase in displacement multiples, clay minerals in the reservoir gradually detach and migrate, reducing the amount of filling and increasing the median radius of rock pore throats. At the same time, the wettability of the rock gradually changes, with a decrease in the oil phase wettability index and an increase in hydrophilicity, resulting in a reduction in the amount of crude oil trapped in the pore throat structure. By regressing the aforementioned 16 sets of experimental data, a chart depicting the variation of residual oil saturation under high displacement multiples was established, as shown in **Figure 2**.

$$S_{or}\left(PV\right) = a\ln\left(PV\right) + b \tag{1}$$

In Equation (1): PV represents the pore volume scouring multiple; a and b are fitting parameters related to rock physical properties and fluid properties.

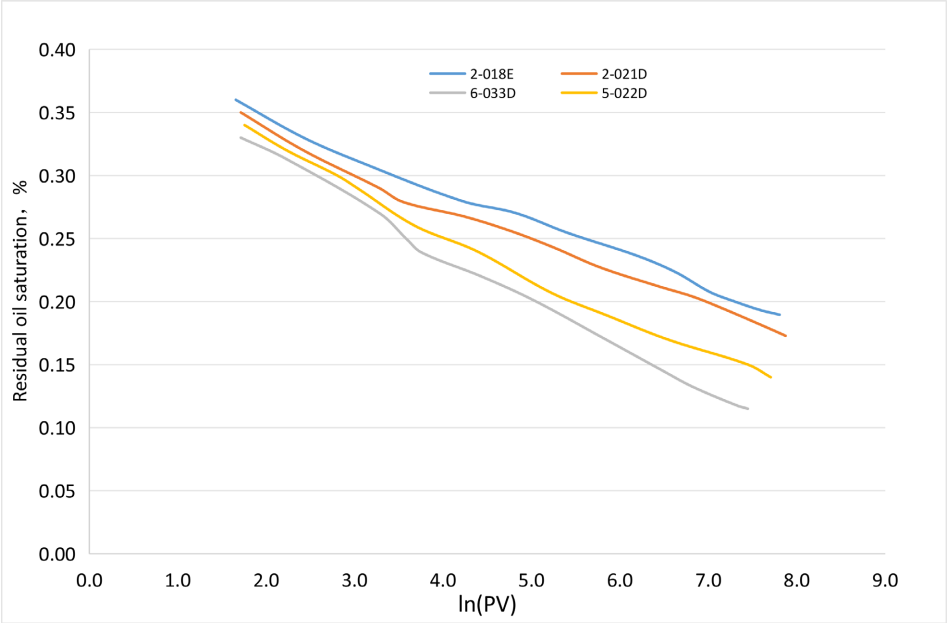


Figure 2. Residual oil saturation variation chart under different displacement multiples.

After fitting the experimental data, the values of a and b under different permeability and crude oil viscosity were obtained (**Figure 3** and **Figure 4**). Residual oil saturation is primarily influenced by pore structure and fluidity variations. Through screening and analysis, expressions for parameters a and b as a function of physical properties and fluidity parameters are established.

$$a = -0.0043\ln\left(K/\Phi\right) - 0.0063 \tag{2}$$

$$b = 0.0239\ln\left(K/\mu\right) + 0.3065 \tag{3}$$

In formula (2), Φ represents the core porosity, *f*. By substituting Equations (2) and (3) into Equation (1), we obtain the empirical formula for the residual oil saturation in the C Oilfield.

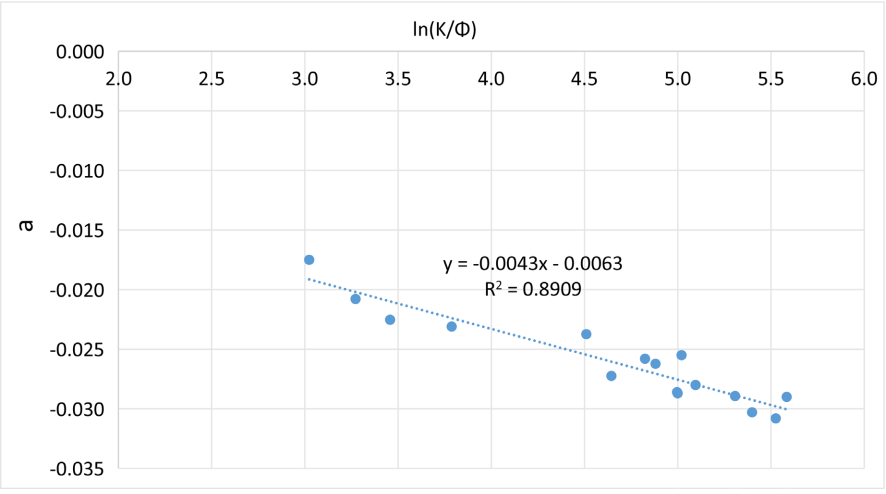


Figure 3. The relationship between the value of coefficient a and the change K/Φ.

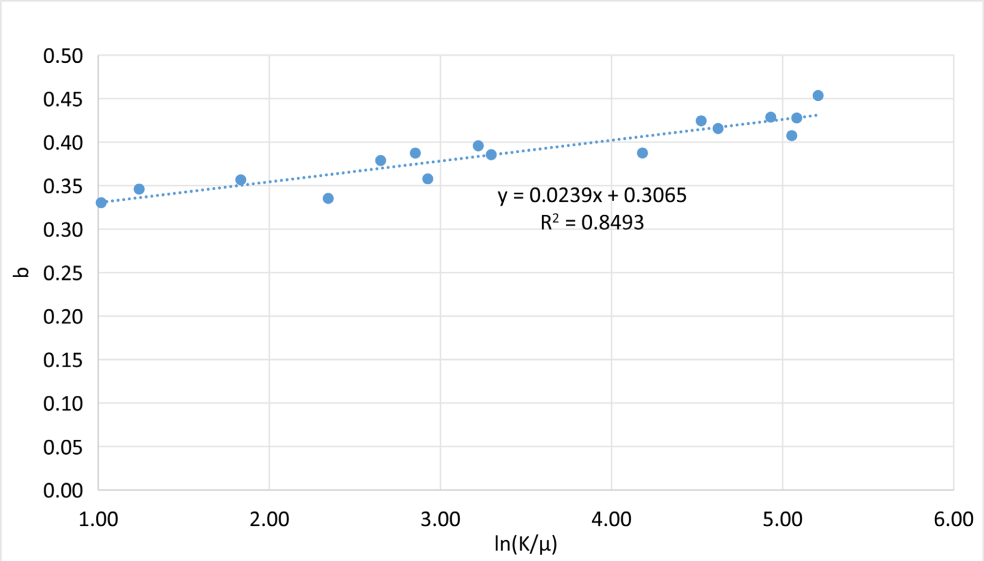


Figure 4. The relationship between the value of coefficient *b* and the change K/μ.

3.2. Dynamic Relative Permeability Characterization Method for Models

Using the Python module in Petrel RE software, the program code is compiled. According to the flow volume of a single grid in each time step, the PV value of a single grid is obtained by dividing it by the grid volume. At the same time, the a and b values of a single grid are obtained by using formulas (2) and (3), which are brought into formula (1) to obtain a single grid, which is brought into the model relative permeability calculation model, and the relative permeability curve series varying with the flow multiple can be obtained. In addition to referring to the fitting rate of the production performance curve, the evaluation of the accuracy of oilfield history fitting is very important to fit and test the saturation of the drilled-through wells, and carry out endpoint time-varying calibration for the residual oil saturation of some through wells.

The key well section for screening should be selected from the passing well sections when the development reaches the ultra-high water cut stage, including sections with low oil saturation, to determine whether it is necessary to increase the time-varying simulation of relative permeability. Subsequently, a comparison is made between the measured saturation of the well section and the saturation fitted in the model. If the measured saturation is lower than the residual oil saturation limit, it indicates that the limit calculation is overly conservative, and the saturation of the well section can be used as the limiting saturation value for constraint; If the measured saturation value is higher than the limit value of residual oil saturation and less than the saturation contained in the model, check whether the local model conforms to the geological understanding, fine-tune the parameters and b value in the dynamic residual oil saturation calculation formula, and test the overall fitting effect after adjustment. The above steps can be cycled to achieve the purpose of iterative modification.

4. Application Effect

4.1. Numerical Simulation Results

Taking the digital analog model of a certain area in the C Oilfield as an example, after fine-tuning and correcting the residual oil saturation formula based on the saturation fitting of key well sections, the saturation of passing wells at the corresponding time points is highly consistent with the actual logging interpretation results (Figure 5); the fitting rate of a single well is more than 90%, and the oil production and water cut of the whole area are well fitted (Figure 6).

According to the detailed geological reservoir description and numerical simulation results, after long-term water drive development, due to the influence of rhythmicity and timely change, the remaining oil in the upper part of the reservoir

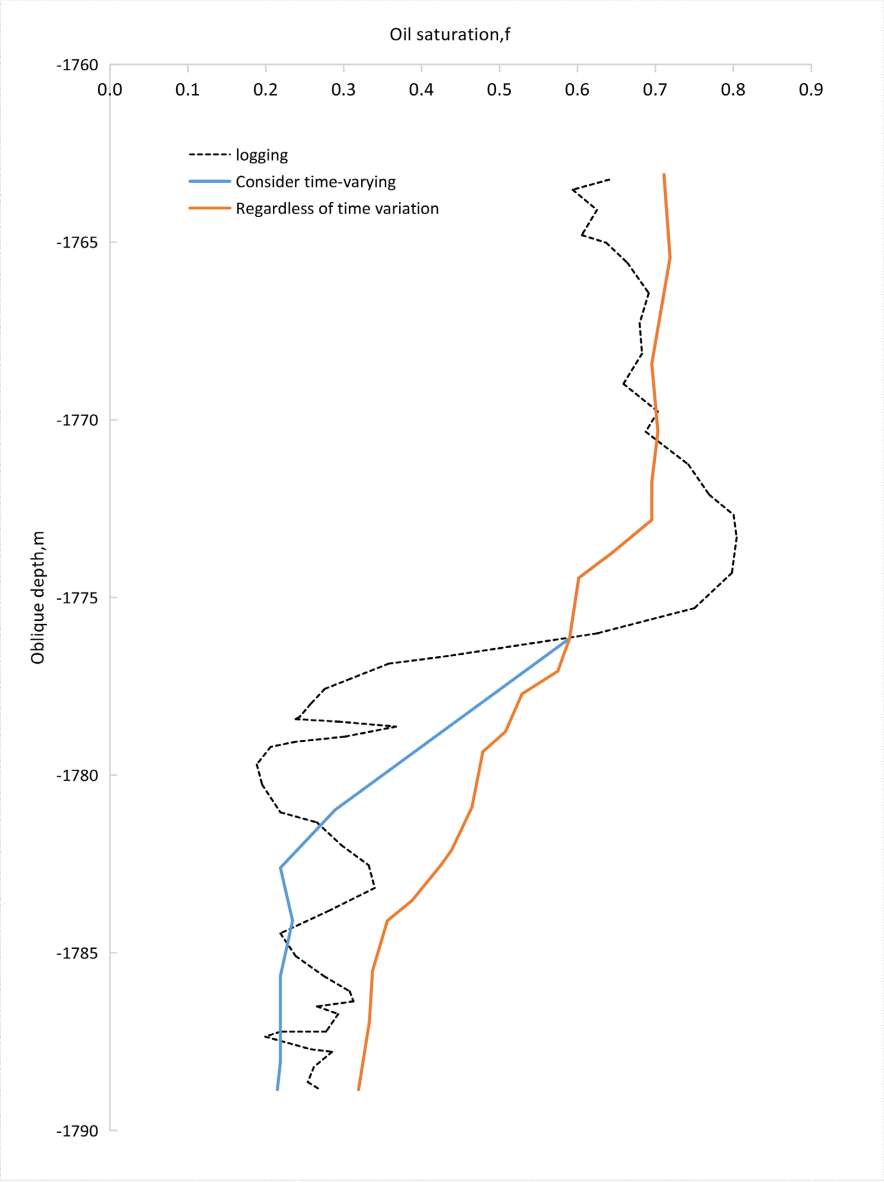


Figure 5. Comparison of oil saturation curves between actual logging and model.

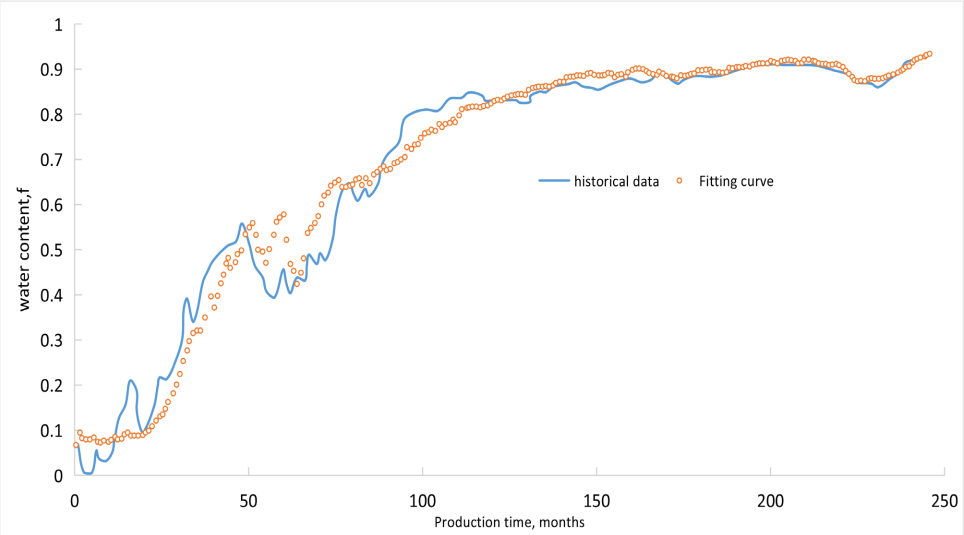


Figure 6. Fitting effect of water cut in the whole area of C Oilfield.

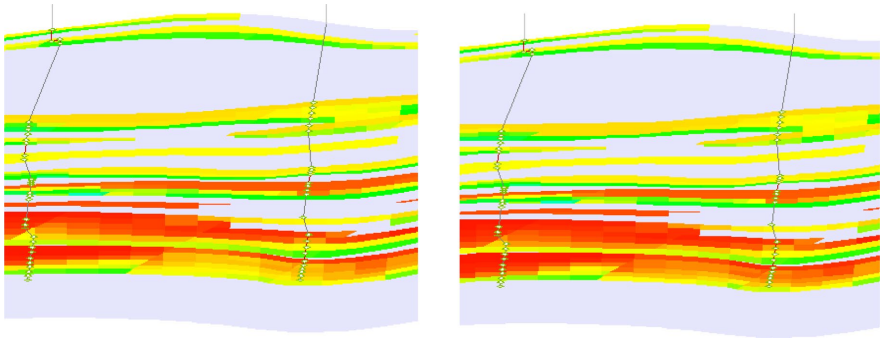


Figure 7. Distribution characteristics of remaining oil without time variation and considering time variation.

is enriched and the bottom is strongly displaced (**Figure 7**). The overall sweep range is reduced, but the displacement intensity in the swept area is high, which is more consistent with the large proportion of weak water-flooded and UN-flooded wells in the crossing section. It is also further confirmed that the reservoir has a remaining oil base for further tapping potential.

4.2. Potential-Tapping Effect

The recovery percentage of a main sand body in C Oilfield reached 16.3%, with a water content of 92% in 2024.Based on the numerical simulation model considering the time-varying relative permeability and the understanding of the remaining oil distribution pattern, utilizing horizontal wells to tap the remaining oil at the top of the inter-well reservoir, six internal infill adjustment wells were implemented. After commissioning, the average initial daily oil production was 50 m^3/d, and the predicted cumulative oil production per well was 6.5×10^4 m^3, achieving good potential tapping results. Meanwhile, based on the latest numerical simulation model, we will re-evaluate the potential of the entire region, laying the foundation for formulating future planning schemes and potential tap-

ping strategies for the oilfield.

5. Conclusion

1) Select 16 sets of typical cores with different permeability and fluid properties from the C Oilfield, and carry out a 2000 PV high-multiple waterflooding experiment. After waterflooding with 2000 PV, the oil displacement efficiency increased by 10.1% to 15.9%, with an average increase of 14.0%. The potential of the high-multiple displacement stage cannot be ignored.

2) In response to the heterogeneous characteristics of reservoir physical properties and fluid properties in C Oilfield, a quantitative characterization formula for residual oil saturation considering physical properties, fluid properties, and displacement multiples has been developed to guide the time-varying law of relative permeability.

3) After considering the time-varying relative permeability, the new model significantly enhances the accuracy and reliability of the simulation. It guides the adjustment and potential tapping of six wells in the oilfield, laying a foundation for the subsequent formulation of planning schemes and potential tapping strategies for the oilfield.

Author Contributions

Sun, E.H. designed the experimental scheme and results analysis; Peng, Q. carried out dynamic relative permeability characterization methods for models and application effects.

Conflicts of Interest

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

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