Application and Calculation Method of Waterflood Front in Low Permeability Reservoir

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1. Introduction

To define the position of waterflood front has important significance for evaluating waterflood development and policy formulation1). To identify the position of waterflood front there are many ways, for example, Buckley-Leverett method, well test analysis, numerical simulation and Micro-seismic test method4). For homogeneous reservoirs, the existing Buckley-Leverett equation (B-L equation) can be used to describe the waterflood front at different time7). But by far the waterflood front variation for low-permeability reservoirs which has strong homogeneity is not so clear. Methods like numerical simulation and micro-seismic test can describe waterflood front dynamic more accurately but they also have cumbersome solving process and costly defects6). Therefore, the introduction of a simple and easy operation method for heterogeneous reservoirs waterflood front is very necessary.

Based on the B-L equation, binding experiments with actual geological data, derive the calculation method which conform heterogeneity characteristics. Experimental and computational methods take a well group in Changqing permeability oilfield as examples to validate the analysis.

Keywords
Low permeability oilfield, Heterogeneity, Waterflood front, Breakthrough timing, Infill wells position

2. Core Composition Experiments

2.1. Experimental Samples and Process

According to the real well pattern (Fig. 1), select corresponding wells around the injection well for coring and chose 6 of them for composition experiments and the permeability ratio is 6 (Table 1). Respectively saturate the core with simulated water and then bound water was made. Finally combine the treated cores to waterflood experiment. The equipment (LSZ) using for the experiment was designed by Institute of Fluid Mechanics, Chinese Academy of Sciences, it can mostly combine 12 cores at one time and simulate the spread characteristics.
between injection well and corresponding production wells in reservoir space through the flow and flooding regularities of cores in different locations. In the experiment, it carries out waterflooding experiment with 12 cores using the ways of multi-layer injection and

| Number | Length [cm] | Diameter [cm] | Permeability [mD] | Porosity [%] | Permeability ratio |
|--------|-------------|---------------|-------------------|--------------|-------------------|
| w1     | 6.082       | 2.525         | 0.2623            | 12.3         |                   |
| w2     | 6.042       | 2.518         | 0.3486            | 13.4         |                   |
| w3     | 6.014       | 2.51           | 0.0739            | 13.7         |                   |
| w4     | 6.013       | 2.519          | 0.1518            | 12.1         |                   |
| w5     | 6.039       | 2.513          | 0.3048            | 14.1         |                   |
| w6     | 4.095       | 2.483          | 0.0594            | 12.7         |                   |
separate layer production.
Through the experiment, we got relative permeability curves of each core and these provide data to support the waterflood front formula for heterogeneous reservoir.

2. 2. Experimental Data Collection
From the experiment we can get that curves about relative permeability and water saturation of 6 cores are quite different (Fig. 3). During the process of waterflooding, the difference in absorption capacity in each direction of strata is very large because of the heterogeneous. That is the main reason why models for high permeability reservoir are not ideal for low permeability reservoir. So we consider dividing the section with different permeability into areas.

2. 3. Creating Formula
According to the well group design (Fig. 1) and assuming that each direction of different permeability, the physical model can be abstracted as Fig. 4.

Based on Buckley-Leverett Eq. (1):

\[ r = \sqrt{n^2 - \frac{f_w(S_{wf})}{\pi d h}} \int_0^Q dt \]  

(1)

To calculate the waterflood front of each area, we need to know the waterflood front water saturation \( S_{wf} \), water content \( f_w \), implicit function \( f_w(S_{wf}) \) about \( S_{wf} \) and water injection of each section. \( S_{wf} \) can be solved through the mapping method.

According to the oil-water relative permeability curves data we get from experiment and fractional flow Eq. (2):

Fig. 3 Oil-water Relative Permeability Curves
Calculated the curves of \( f_w \) and \( S_w \), make a tangent line to \( f_w \) through \( S_w \) and they intersect a point. Make a perpendicular line through the point to horizontal axis cross at a point and it is just the value of \( S_w \) and then programmed to calculate \( f_w \) and \( S_w \) (Fig. 5).

Finally, according to \( S_w \), the water phase and oil phase relative permeability \( (k_wr, k_oo) \) can be solved through interpolation method (Table 2).

According to splitting formula:

\[
\eta_i = \frac{1}{1 + \frac{\mu_w}{\mu_o} \frac{k_{iw}}{k_{ow}}} - \left( \frac{(kk_{rw})}{\mu_w} + \frac{(kk_{ro})}{\mu_o} \right) \sum_{i=1}^{N} \left( - \frac{(kk_{rw})}{\mu_w} + \frac{(kk_{ro})}{\mu_o} \right)
\]

Absorption amount of each partition can be calculated. Substitute the obtained data talking above into Eq. (1), then we get the moving position of waterflood front from one to six years (Table 2 and Fig. 6).

### Table 2 Computing Result of Waterflood Front

|       | \( k_{rw} \) | \( k_{ro} \) | 1 year [m] | 3 years [m] | 6 years [m] |
|-------|--------------|--------------|------------|-------------|-------------|
| w1    | 0.093        | 0.052        | 54.73      | 91.21       | 121.62      |
| w2    | 0.104        | 0.069        | 110.21     | 183.69      | 244.92      |
| w3    | 0.092        | 0.051        | 23.24      | 38.74       | 51.65       |
| w4    | 0.077        | 0.021        | 40.82      | 68.03       | 90.71       |
| w5    | 0.053        | 0.002        | 61.00      | 101.66      | 135.55      |
| w6    | 0.062        | 0.002        | 23.09      | 38.48       | 51.31       |

2.4. Formula Examination and Prediction of Waterflood Front

According to the calculation result, advantage water injection direction of the experiment well group is the north-south axis northeast direction 40° and it perfectly matches the micro-seismic test map which achieved after 5 years when the well group went into production (Fig. 6). One step further, as we predicted, w1 at the
point 50 m from the injection well and after 3 years, w1 first enter the breakthrough time. And after 6 years, w2 gets its water breakthrough time. And we can plan that the infill wells can be drilling at the direction of w3 and w6.

Compared with the result which uses the traditional B-L equation (Fig. 7), after 3 years, all production wells get their breakthrough times and it is vary widely with the actual data.

3. Conclusion

(1) Combined with the experiments and actual field data, a new method for heterogeneous reservoir water-flood front calculation was proposed. Results show that advantage water injection direction of the experiment well group is the north-south axis northeast direction 40° and it perfectly matches the micro-seismic test map.

(2) Predicting the waterflood front, w1 first enter the breakthrough time. And after 6 years, w2 gets its water breakthrough time. The proposed drilling location of infill wells are the direction of w3 and w6.

(3) Compared with the result which uses the traditional B-L equation, the new method is much more accurate.

(4) With the increase in simulation time and the partition refinement, the results will be more accurate.

Nomenclatures

\[ f_w : \text{rate of water content} \]  
\[ h : \text{effective thickness of reservoir} \]  
\[ k_{ro} : \text{oil-phase relative permeability} \]  
\[ k_{rw} : \text{water-phase relative permeability} \]  
\[ k_{rwe} \text{ and } k_{roe} : \text{especially for the waterflood front} \]  
\[ Q : \text{daily water-injection rate} \]  
\[ R_e : \text{radius of edge} \]  
\[ r_w : \text{waterflood front} \]  
\[ S_w : \text{water saturation} \]  
\[ \phi : \text{porosity} \]  
\[ \mu_w : \text{water-phase viscosity} \]  
\[ \mu_o : \text{oil-phase viscosity} \]  

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