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Application and Calculation Method of Waterflood Front in Low Permeability Reservoir

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Waterflood front dynamic has important significance in evaluating waterflooding effect. It also guides the design of well pattern infilling, the adjustment of infilling and the waterflood method. Modelling heterogeneity (if any) is an important factor in any geological and reservoir simulation model. The proper estimation of waterflood front is highly depending on geologic modelling able to capture heterogeneous feature of reservoir. Combined with core composition experiments and actual field data, a new method for heterogeneous reservoir waterflood front calculation was proposed depending on the equation of Buckley-Leverett. Using this method to calculate well group of Wangyao oilfield, distribution of waterflood front and water breakthrough time of production wells were predicted, position of infill wells drilling was proposed and the results show that they were perfectly matched with the micro-seismic test data. When calculating the same well group with the homogeneous model, the error is large. The new calculation method has the advantages of simple and convenient operation, strong practicability and it functions just like a calculator to people that can easily identify the movement trend of the waterflood front which can not be achieved in numerical simulation or other calculation method.

Keywords

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

1. Introduction

To define the position of waterflood front has important significance for evaluating waterflood development and policy formulation^{1)~3)}. 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 method^{4)~6)}. 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 defects⁸⁾. 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.

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**). The experimental temperature are 50 °C, using simulated formation water and simulated oil with viscosity 2.1 mPa s in 50 °C. Respectively saturate the core with simulated water under pressure, after that saturate the core with simulated oil and then bound water was made. Finally combine the treated cores to waterflooding experiment. Experimental process is in **Fig. 2**.

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

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Fig. 2 Experimental Flow Chart of LSZ

Fig. 1 Well Location of Experimental Well Group

Table 1 Basic Physical Properties of Experimental Rock Sample

Number	Length [cm]	Diameter [cm]	Permeability [mD]	Porosity [%]	Permeability ratio
w1	6.082	2.525	0.2623	12.3	6
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	

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

Fig. 3 Oil-water Relative Permeability Curves

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):

$$r_1 = \sqrt{r_0^2 - \frac{f'_w(S_{wf})}{\pi \phi h} \int_0^t Q dt} \quad (1)$$

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. 4 Simulation Partition of Experimental Well Group

Fig. 5 Waterflood Front Water Saturation Calculation

$$f_w = \frac{1}{1 + \frac{\mu_w k_{ro}}{\mu_o k_{rw}}} \quad (2)$$

Calculated the curves of f_w and S_w , make a tangent line to f_w through S_{wf} 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_{wf} 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_{rw} and k_{ro}) can be solved through interpolation method (Table 2).

According to splitting formula:

$$\eta_i = \frac{-\left(\frac{(kk_{rw})_i}{\mu_w} + \frac{(kk_{ro})_i}{\mu_o}\right)}{\sum_{i=1}^{i=N} \left[-\left(\frac{(kk_{rw})_i}{\mu_w} + \frac{(kk_{ro})_i}{\mu_o}\right)\right]} \quad (3)$$

Absorption amount of each partition can be calculated. Substitute the obtained data talking above into Eq.

Table 2 Computing Result of Waterflood Front

Number	k_{rwe}	k_{roe}	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

(1), then we get the moving position of waterflood front from one to six years (Table 2 and Fig. 6).

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

Fig. 7 Result of the Original B-L Equation

Fig. 6 Distribution of Waterflood Front and Micro-seismic Test Map

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 waterflood 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	: rate of water content	[%]
h	: effective thickness of reservoir	[m]
k_{ro}	: oil-phase relative permeability	[mD]
k_{rw}	: water-phase relative permeability	[mD]
k_{rwe} and k_{roce}	: especially for the waterflood front	[mD]
Q	: daily water-injection rate	[m ³ /d]
R_o	: radius of edge	[m]
r_i	: waterflood front	[m]
S_w	: water saturation	[%]
S_{wf}	: water saturation for waterflood front	[%]
S_{wr}	: irreducible water saturation	[%]
<Greeks>		
ϕ	: porosity	[%]
μ_w	: water-phase viscosity	[mPa s]
μ_o	: oil-phase viscosity	[mPa s]

References

- 1) Yan, J. H., Xu, Y. N., Zhu, L. H., *Fault-Block Oil & Gas Field*, **12**, (6), 59 (2005).
- 2) Liu, H. Y., Cheng, S. L., Huang, S. J., *Journal of Chongqing University of Science and Technology: Natural Science Edition*, **11**, (3), 34 (2009).
- 3) He, X. W., Yang, L., Liu, Y., *Natural Gas and Oil*, **29**, (2), 54 (2011).
- 4) Zhao, Y. F., Xu, B., *Inner Mongolia Petrochemical Industry*, **36**, (9), 124 (2010).
- 5) Jupe, A., Cowles, J., *World Oil*, **219**, (12), 171 (1998).
- 6) Guo, Z. H., *Inner Mongolia Petrochemical Industry*, **8**, 137 (2013).
- 7) Feng, X., *Well Testing*, **3**, (2), 28 (1994).
- 8) Jia, J. W., Zhang, W., *Journal of Chongqing University of Science and Technology: Natural Science Edition*, **15**, (1), 104 (2013).