New Water-Oil Displacement Efficiency Prediction Method

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Abstract: There is seldom research on describing the changing trend of water-oil displacement efficiency based on time and water drive frontal position. In previous study, our team gave the theoretical expression of water saturation in oil-water fluid flow area based on time and distance. In this work, we mainly focus on the prediction of water-oil displacement efficiency combining the permeability experiment and theoretical expression of water saturation. This new expression gives the micro water-oil displacement efficiency in different frontal position and time. The prediction results show: that the predicting accuracy is high and practicable, and we can shorten the time and cost of experiment and this prediction method is meaningful in guiding the actual oilfield development.

INTRODUCTION

Buckley-Leverett (1942) proposed the Buckley-Leverett equation [1], and it has been used in water saturation prediction experimentally, so theoretical expression of water saturation based on time and distance needs to be established. Many scholars are engaged in water saturation description, and already made some progress. The previous study was based on the experimental method, Archie (1942) established a formula of water saturation adaptive to these pure sandstone reservoirs [2]; Poupon's work (1971) [3] was based on Simandoux's which was done in 1983 [4], where an equation of water saturation was given. Fertl (1982) [5] and Dewan (1998) [6] further developed the above-mentioned equation. Yao (1993) *et al.* used the analytical forecasting method to study the water saturation of reservoir [7]; Zhang *et al.* (2008) theoretically deduced the relation between electric resistivity and water saturation [8]; Wang *et al.* (2010) [9] and Li (2010) [10] also studied the water saturation of oil reservoirs with the experimental method, respectively. However, the theoretical expression of water saturation based on time and distance still needs to be studied. Considering the Buckley-Leverett equation and related mathematical model, and introducing Vieta's theorem to the differentiation of water cut, Liu [11, 12] established the theoretical expression of water saturation based on time and distance. This new expression can be used to predict the water-oil displacement efficiency. At present, there is seldom theoretical research on water-oil displacement efficiency prediction method based on time and distance. Hence, study on water-oil displacement efficiency based on time and distance gets theoretical and practical value.

PARAMETERS CONFIRMATION IN NEW WATER SATURATION EQUATION

Combining relational expression between relative permeability and water saturation with the fractional flow equation

produced an expression of water cut changed by water saturation; Introducing Vieta's theorem to the differentiation of water cut gave a theoretical expression of water saturation in oil-water fluid flowarea; Introducing the concept of frontal water saturation to these expressions gave the continuous expression of water saturation [12], it is,

$$S_w = \frac{1}{b} \ln \left(2\phi A(x-x_0)Ma \Big/ \begin{array}{l} -[2\phi A(x-x_0) - bW(t)] + \\ W(t)\sqrt{b[b - \frac{4\phi A}{W(t)}(x-x_0)]} \end{array} \right), \quad (1)$$

$$\frac{bW(t)}{2\phi A(Ma+1)} \le x - x_0 \le \frac{bW(t)}{4\phi A}$$

$$S_w = \frac{1}{1.52} \ln \frac{1880.8(x-x_0)}{45.6t - 420(x-x_0) + 30t\sqrt{2.3104 - \frac{42.56(x-x_0)}{t}}]},$$
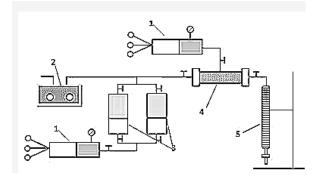
$$0.01982t \le x - x_0 \le 0.0543t$$

By taking the relative permeability experiments, the parameter of *a* and *b* in eq. (1) can be achieved with regression analysis method, the experiment procedure is given in Fig. (**1**).

Experiment steps:

1) Drill and cut cores;

2) Preparation of formation water and simulated oil;

3) Clean and load cores;

4) Measurement of air and water permeability;

5) Calculation of pore volume;

6) Establishment of irreducible water saturation;

7) Measurement of oil relative permeability;

8) The experimental data processing;

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9) Simulation of parameters *a* and *b* with regression method.

1-Displacement pump; 2-Vacuum pump; 3-Intermediate container; 4-Core holder; 5-oil and water metering device

Fig. (1). Relative permeability experiments procedure.

PREDICTION OF WATER-OIL DISPLACEMENT EFFICIENCY

Prediction of Water-Oil Displacement Efficiency

Definition of water-oil displacement efficiency gives

$$E_D = \frac{S_w - S_{wr}}{1 - S_{wr}} \tag{2}$$

In previous time, the E_D was changed by S_w, and in calculation, we can hardly obtain the micro water-oil displacement efficiency in different water drive front position. By introducing eq. (1) to eq. (2) gives

$$E_D = \frac{\frac{1}{b}\ln\left(\frac{2\phi A(x-x_0)Ma}{-[2\phi A(x-x_0)-bW(t)]+W(t)\sqrt{b[b-\frac{4\phi A}{W(t)}(x-x_0)]}}\right) - S_{wr}}{1 - S_{wr}} \tag{3}$$

so we can use eq. (3) to calculate the E_D chanced by time and distance. In other word, the E_D in any water drive front position and time can be predicted now.

Prediction of Water Cut

It is known to us, one regression expression between permeability and saturation is,

$$\frac{k_{ro}}{k_{rw}} = ae^{-bS_w} \tag{4}$$

Here, $\frac{k_{ro}}{k_{rw}}$ is the ratio of oil permeability and water permeability, a and b are regression parameters.

Definition of water cut shows:

$$f_w = \frac{Q_w}{Q_w + Q_o} = \frac{K_w/\mu_w}{K_w/\mu_w + K_o/\mu_o} = \frac{1}{1+\left(\frac{K_o}{K_w}\right)\left(\frac{\mu_w}{\mu_o}\right)} \tag{5}$$

By introducing eq. (1) and eq. (4) to eq. (5) gives

$$f_w = \frac{1}{1+ae^{-b\left[\frac{1}{b}\ln\left(\frac{2\phi A(x-x_0)Ma}{-[2\phi A(x-x_0)-bW(t)]+W(t)\sqrt{b[b-\frac{4\phi A}{W(t)}(x-x_0)]}}\right)\right]}\left(\frac{\mu_w}{\mu_o}\right)} \tag{6}$$

Eq. (6) can be used to depict water cut changed by time and frontal distance, further, we can analyze the relation between water cut and water-oil displacement efficiency.

APPLICATION AND DISCUSSION

Given the experimental data of certain sandstone oil reservoir, see Table **1** and Table **2**.

In Fig. (**2**), the bold line is the simulation line and the thin blue line is the experiment line, the simulation line is close to the experimental line;

In Fig. (**3**), the regression accuracy curve shows the simulation accuracy is higher than 0.97, in other word, the regression error is 0.03, this is acceptable. Here, In a=9.52374, b=16.2878. Using eq.(3) and eq.(5) gives Fig. (**4**) and Fig. (**5**):

Fig. (**4**) and Fig. (**5**) show: (1) the water in the block appears early, the time of oil production without water is short; the water cut improves quickly in the stage of water drive;

Table 1.   **Water and oil permeability data of a sandstone oil reservoir.**

S_w, %	0	10	20	30	40	50	60	70	75	80	90	100
K_{ro}	1	1	1	0.94	0.80	0.44	0.16	0.045	0	0	0	0
k_{rw}	0	0	0	0.01	0.04	0.11	0.20	0.30	0.36	0.44	0.68	1

Table 2.   **Practical development data of a sandstone oil reservoir.**

Velocity Ratio of Oil and Water	Porosity	Reservoir Width, m	Formation Thickness, m	Single Well Production, m^3/d	Residual Oil Saturation	Irreducible Water Saturation
5	0.25	140	6m	30	0.28	0.25

By using regression method gives

the water cut improves slowly in the late stage of water drive; the effect of flooding is poor. (2) detailed changing trends of E_D and f_w are given. (3) the predicting result of E_D is consistent with the experimental result of E_D in water flood front position.
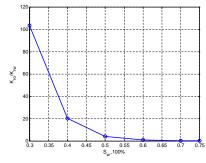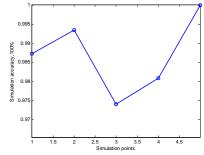

Fig. (2). Regression figure between Kro/Krw and Sw.
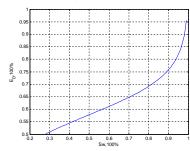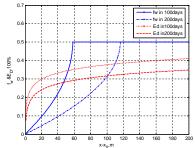

Fig. (3). Regression accuracy.

Fig. (4). The curve between water-oil displacement efficiency and water cut.

Fig. (5). E_D and f_w changed by time and frontal distance.

Here, the blue and pink curves are the curves on E_D in 100 and 200days, separately; and the yellow triangle and the green intersect curves are the curves on f_w in 100 and 200 days, separately.

Generally, the water in the block appears early, the oil and water production period is short, the water cut rises fast, the water channeling is severe and the water-oil displacement efficiency is low.

Note: The new E_D prediction method is based on time and frontal position, it belongs to the microscopic percolation mechanism. While, the previous water-oil displacement efficiency prediction methods are based on water saturation or water cut, they belong to the macroscopic percolation mechanism.

CONCLUSION

1. New water-oil displacement efficiency and water cut predicting methods are changed by time and water flood frontal position.

2. The predicting result of E_D is consistent with the experimental result of E_D in water flood front position. The predicting accuracy is high and practicable, and we can shorten the time and cost of experiment and guide the practical development of oil field.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

NOMENCLATURE

k_o = Oleic permeability, mD

k_w = Water phase permeability, mD

a = Linear intercept

b = Linear slope

f_w = Water cut or fractional flow rate

M = Viscosity ratio of water and oil

ϕ = Porosity

A = Seepage flow area, m

S_{or} = Residual oil saturation

S_{wr} = Irreducible water saturation

x_f = Location of frontal zone, m

E_D = Water-oil displacement efficiency

$\dfrac{\partial f_w}{\partial S_w}$ = Ratio of change in water cut to change in saturation

$x - x_o$ = Forwarding distance of any constant water saturation in seepage area, m

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