Petroleum 1 (2015) 158–163

Contents lists available at ScienceDirect

Petroleum

journal homepage: www.keaipublishing.com/en/journals/petlm

Original article

Characterization of pore volume of cumulative water injection distribution

Guoqing Feng [a], MingLe Yu [b,*]

[a] State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation, Southwest Petroleum University, Chengdu City, Sichuan Province 610500, China
[b] Southwest Petroleum University, Chengdu City, Sichuan Province 610500, China

ARTICLE INFO

Article history:
Received 17 March 2015
Accepted 31 March 2015

Keywords:
Water drive reservoir
Cumulative water injection pore volume
Numerical flow simulation
Inflection point
Limit point
Recovery factor

ABSTRACT

Pore volume of Cumulative water injection is one of the factors for evaluating water flood effect in a water flood oil field. In previous study, there were limited lab studies for evaluating oil displacement efficiency. A method to characterize the distribution of pore volume of cumulative water injection is proposed in this paper, and it is verified by a five-spot water flooding streamline simulation model. The logarithmic relation between pore volume of cumulative water injection and water saturation is established by regression. An inflection point and limit point of cumulative water injection pore volume are identified. Current simulation model indicates inflection point appears after 2–5 pore volume (PV) injection, and limit point appears after 15–25 PV injection. Both inflection and limit point vary in different regions of reservoir.

1. Introduction

For most water flood oil fields, especially in the later stage of water flooding, the water displacement efficiency and economic outcome of water flooding decrease due to reservoir geological and fluid characters. For example, reservoir heterogeneity and imbalance of injection–production cause uneven water front; viscosity difference between the oil and injected water result in viscous fingering towards producers. In addition, capillary pressure and fracture may further complicate water flood behavior. Better understanding the relationship between cumulative water injection and water saturation distribution at high water cut stage is critical for accurate production prediction, infill drilling and production optimization. Many studies have been done to help understand the behavior of later stage water flooding [1] and [2] et al.).

Liu and Wu [1] established a linear equation between water saturation and cumulative water injection pore volume based on Darcy's law. Based on Buckley–Leverett equation [3], built a logarithmic correlation between residual oil saturation and the cumulative water injection pore volume [4]. developed an analytical method to calculate the streamline distribution and water cut of a producer in injection–production patterns before and after the water breakthrough [5]. Obtained water cut variation law with injected pore volume multiplied by physical experiments of water displacing oil [2]. Proposed that the changes of wettability and pore structure in a high water-cut stage would improve water–oil displacement efficiency.

In the previous studies, only cumulative water injection pore volume was considered, which is defined as ratio of well cumulative water injection to reservoir pore volume. It can not characterize spatial distribution of the water flood effect in different region of a reservoir. In this paper, the method to characterize the distribution of pore volume of cumulative water injection by reservoir numerical simulation has been proposed and the relationship between water saturation and cumulative water injection pore volume has also been studied.

In this paper, the method and workflow is first introduced. It is followed by a streamline simulation study of a synthetic 2D reservoir model. An empirical relationship and its implication are discussed.

* Corresponding author.
E-mail address: 1030019049@qq.com (M. Yu).
Peer review under responsibility of Southwest Petroleum University.

Production and Hosting by Elsevier on behalf of KeAi

http://dx.doi.org/10.1016/j.petlm.2015.03.007

2. Methodology

The cumulative water injection pore volume M is defined as the ratio of cumulative water injection through each grid block to the pore volume of that grid block in reservoir numerical simulator.

$$M = \frac{W_f}{V_p} \tag{1}$$

where M is the cumulative water injection pore volume, V_p is the grid block pore volume, W_f is the cumulative water injection through that grid block. In reservoir numerical simulator, in three dimension space, cumulative water injection of grid block (i, j, k) are the summation of water flow rate Q_{wx}, Q_{wy}, Q_{wz} at each time step. Q_{wx}, Q_{wy}, Q_{wz} are the water rate through the grid block in each direction. In fact, for each grid block, in each direction, there exist two water flow rate (inflow rate and outflow rate), which can be calculated by the following modified Darcies equation (Fig. 1):

$$\begin{aligned}
Q_{wx+} &= \frac{K_{i,j,k}}{\Delta x}\cdot\left[\frac{K_{rw}}{\mu_w}\right]_{i+1,j,k}\left(p_{i+1,j,k} - p_{i,j,k}\right)\\
Q_{wx-} &= \frac{K_{i,j,k}}{\Delta x}\cdot\left[\frac{K_{rw}}{\mu_w}\right]_{i,j,k}\left(p_{i,j,k} - p_{i-1,j,k}\right)\\
Q_{wy+} &= \frac{K_{i,j,k}}{\Delta y}\cdot\left[\frac{K_{rw}}{\mu_w}\right]_{i,j,k}\left(p_{i,j+1,k} - p_{i,j,k}\right)\\
Q_{wy-} &= \frac{K_{i,j,k}}{\Delta y}\cdot\left[\frac{K_{rw}}{\mu_w}\right]_{i,j,k}\left(p_{i,j,k} - p_{i,j-1,k}\right)\\
Q_{wz+} &= \frac{K_{i,j,k}}{\Delta z}\cdot\left[\frac{K_{rw}}{\mu_w}\right]_{i,j,k}\left(p_{i,j,k+1} - p_{i,j,k}\right)\\
Q_{wz-} &= \frac{K_{i,j,k}}{\Delta z}\cdot\left[\frac{K_{rw}}{\mu_w}\right]_{i,j,k}\left(p_{i,j,k} - p_{i,j,k-1}\right)
\end{aligned} \tag{2}$$

where grid (i+1, j, k), (i, j+1, k), (i, j, k+1) are the upstream of (i, j, k) grid block and grid (i+1, j, k), (i, j+1, k), (i, j, k+1) are the downstream of (i, j, k). At each time step, the sum of Q_{wx}, Q_{wy}, Q_{wz} is the water flow rate Q_w. So the cumulative water injection can be determined by the following equation:

$$W_f = \sum_0^t Q_w \tag{3}$$

In the process of reservoir numerical simulation, Q_{wx}, Q_{wy}, Q_{wz} at each time step can be recorded. Then using the equation

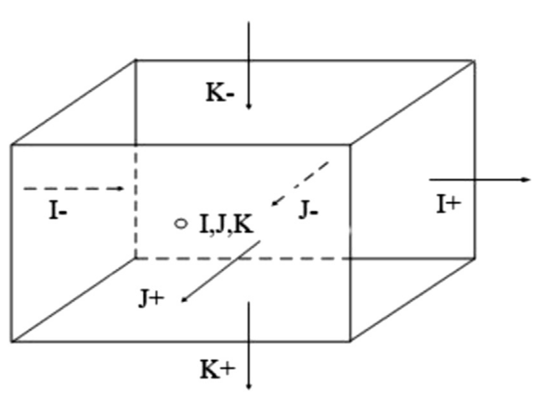

Fig. 1. Sketch of fluid flow in the grid.

(3), W_f can be calculated. V_p is the grid block pore volume, which is defined by grid volume, porosity and grid net to gross in reservoir condition. By using equation (1), M of every grid block can be calculated.

3. A five-well simulation model

A synthetic 2D flow simulation model is constructed for this study. Following is a brief introduction of the static model As shown in Table 1, the dimensions of the model are approximately 1000 × 1000 m, The average thickness is 5 m, and the average porosity is 20%. The model is represented with 100 × 100 × 1 gridblocks.

It is a five-spot water flood pattern with one injector well in the center and four producers around it, as shown in Fig. 2. Water injection rate is assigned to be 200 m^3/d rate, and the four oil wells each produce 50 m^3/d liquid.

After 500 days, cumulative water injection pore volume M of each grid in the model can be calculated. In each grid block, the cumulative water injection is calculated by equation (3), then cumulative water flood pore volume M can be calculated by equation (1). In the grid block penetrated by a well, W_f should be equal to the cumulative water production rate for producers and be equal to the cumulative water injection rate for injector respectively. Table 2 is the difference between them, and the results show that the relative error is less than 1%. Therefore, Equation (3) is practicable for the calculation the cumulative water flow rate.

In addition, cumulative inflow rate and outflow rate of each grid block can also be calculated by equation (3). As a result, there is little difference between cumulative inflow rate and outflow rate in four arbitrary grid blocks shown in Table 3. For a certain grid, with the grid block size become smaller, the difference between cumulative inflow rate and outflow rate will be smaller too. Therefore cumulative inflow rate or outflow rate can also be used in the actual calculation.

The distribution of M after 500 days is plotted as shown in Fig. 3. It shows that M is high in the grid block around the injection well, almost equal to 100, and in the grid block near the producers, M is also high. In the region between injection well and production wells, M is relatively low. Simultaneously, in the region of main stream line between injector and producers (Fig. 4), M is also high. FrontSim simulation result is shown in Fig. 4. The distribution of streamline is similar with M. In the region which the streamline is dense, M is high.

M values in nine grid blocks shown in Fig. 5 have been analyzed. From grid ‘P1’ to grid ‘P9’, the grid block is gradually close to the main stream direction between producer ‘prod-1’ and injector ‘inj-1’. The comparison of M in nine grid blocks is shown in Table 3. From “P1” to “P9”, M gradually increase. M value in “P9” is 35.2, which is almost 5 times of that in “P1”. The grid is closer to the mainstream direction, the higher M is, and vice versa. The reason is that fluid always preferentially flows along mainstream direction, where the pressure gradient is

Table 1
Reservoir simulation model input parameters.

Reservoir properties	
Reservoir dimension	1000 m × 1000 m
Thickness	5 m
Initial reservoir pressure	21 MPa
Porosity	20%
Fluid properties	
Initial Viscosity	6.8 mpa s
Initial Compressibility	0.002 MPa^{-1}

Table 2
Comparison of calculated flow rate and the actual flow rate.

Well name	Well type	Calculated cum. Water injection rate (m^3)	Cum. Water production rate/water injection rate (m^3)	Relative error (%)
INJ-1	Injection well	99,294	100,000	0.71
PROD-1	Production well	18,848	18,982	0.71
PROD-2	Production well	15,197	15,322	0.82
PROD-3	Production well	14,970	14,839	0.87
PROD-4	Production well	19,197	19,340	0.73

greater than the one at any other direction, which is also controlled by the reservoir permeability distribution.

4. The relationship between M and S_w

In a grid block, when water flood through, mobile oil in the block is displaced, which changes the water saturation of the grid block. Generally, with the increasing of cumulative water injection, water saturation increases. The five-spot flow simulation model is simulated for 20 years in order to establish the relationship between M and water saturation S_w. The relationship between S_w and M of grid P5 is shown in Fig. 6. It shows that with the increase of M, S_w rises rapidly at first; then when M reaches a certain value (2.5 P V in this case), the rise of S_w slow down. The turning point is named as 'inflection point' cumulative water injection pore volume, or simply inflection point in this paper. At last, S_w almost doesn't change with the increase of M, this value of M is named as 'limit point' of cumulative water injection pore volume, or limit point for brevity. In Fig. 6, when M reaches to 12 P V, water cannot displace the oil of grid block and water flooding with existing production strategy is no longer valid. Infill drilling, alternative EOR or abandonment decisions need to be made.

The regression curve of M and water saturation S_w in grid P_5 is also shown in Fig. 5. It can be fitted as logarithmic curve: $S_w = 0.0243\ln M + 0.4573$, logarithmic curve reflect the change of S_w with the increment of M. Water saturation rises rapidly at early stage, then rises slowly and flat out at last. The logarithmic type relationship between M and S_w is in agreement with the experiment observation by Ref. [3].

A logarithmic curve is established to model the relationships between M and S_w in other gird blocks shown in Table 4.

Table 3
Comparison of cum. water inflow and outflow rate through arbitrary grid.

Grid	Inflow (m^3)	Outflow (m^3)	Difference (m^3)
P1	652	626	26
P2	761	750	11
P3	353	342	11
P4	576	562	14

Table 4
Comparison of M in different grid blocks.

Grid	P9	P8	P7	P6	P5	P4	P3	P2	P1
M(PV)	35.2	33.5	28.9	22.3	17.7	14.9	12.7	10.1	7.8

$$Sw = A\ \ln M + B \tag{4}$$

Parameter A, B, 'inflection point' and 'limit point' cumulative water injection pore volume in other grid blocks are shown in Table 5. Parameter A and B have a little difference in different grid blocks. Due to this, 'inflection point' and 'limit point' are also different. Among the nine grid blocks, 'inflection point' ranges from 2 to 5 PV and the 'limit point' is 15–25 P V. In the process of water flooding, due to various reasons such as reservoir heterogeneity, oil-water viscosity contrast, difference of injection-production ratio in different region etc., parameter A and B are different, and it leads to the difference of 'inflection point' and 'limit point' cumulative water flood pore volume.

Understanding the inflection point and limit point are very import for water flooding forecasting and production optimization. When M reaches to inflection point, it means that most of oil in the grid block has been driven, only the small amount of oil remains in it; (or injection water breaks through and reaches producers, significant water cut increase and reduction of water displacement efficiency is expected); and when M equals to limit point, it means that mobile oil has been flooded along flow path. Continue water flooding with existing production strategy is no longer valid. Decisions such as infill drilling, alternative EOR or abandonment need to be made.

In different region of a reservoir after many years water flooding, if relationship between M and S_w can be established, then 'inflection point' and 'limit point' can be determined. According to this, at the region where M is less that inflection point, water injection rate should be increased, and at the region where

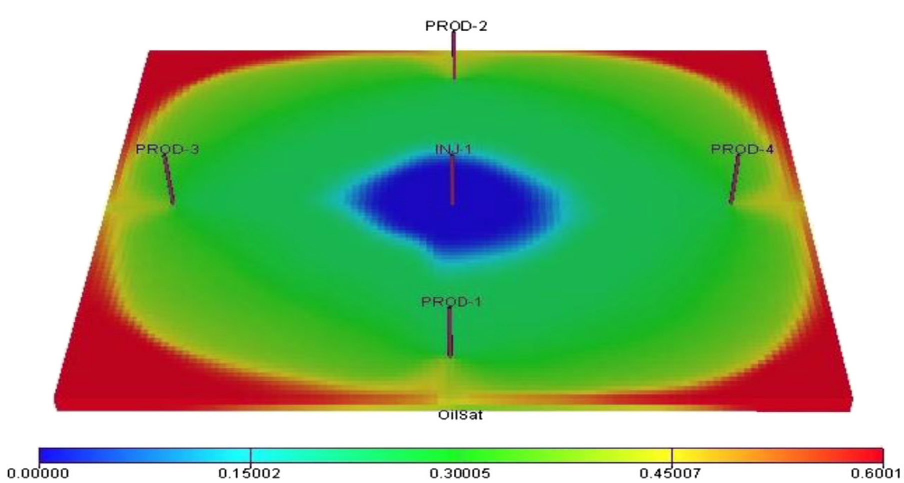

Fig. 2. A five-well group simulation model (oil saturation).

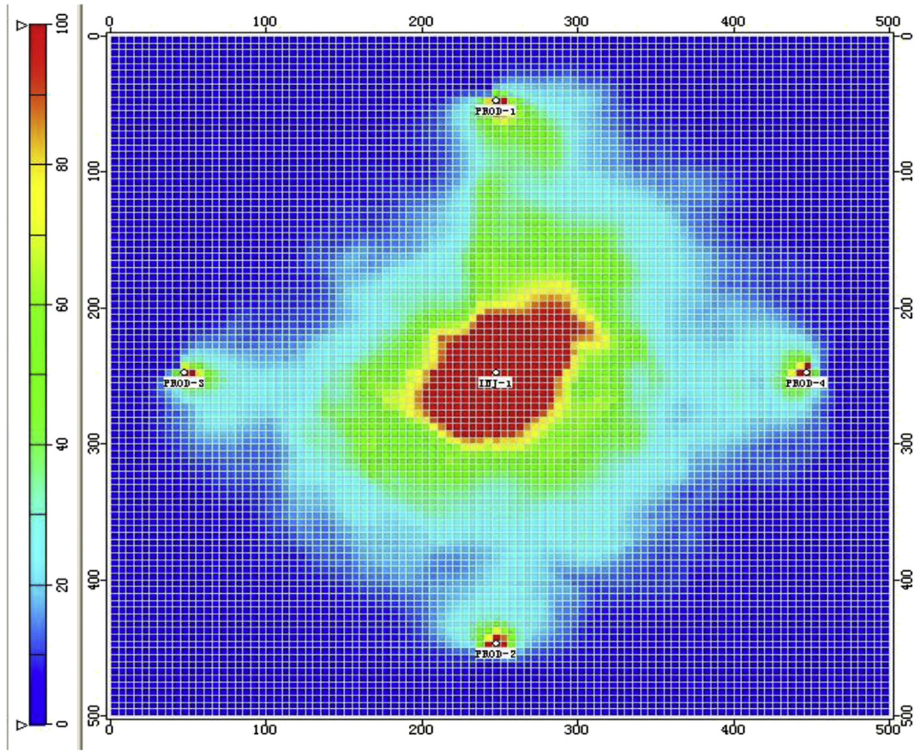

Fig. 3. Distribution of M (500 d).

M is larger than limit point, water injection in not useful and water injectors should be shut in.

The relationship between M and S_w can be used to guide water flooding at high water cut reservoir. For water flooding reservoir, after reservoir flow simulation work has been finished, the distribution of M can be calculated, and the relationship between M and S_w can be established. As a result, inflection point and limit point in different regions of reservoir can also be determined, which can be used to allocate injection volume and production optimization.

5. Conclusions

(1) This paper proposes a method to characterize the distribution of cumulative water injection pore volume based on reservoir simulation.

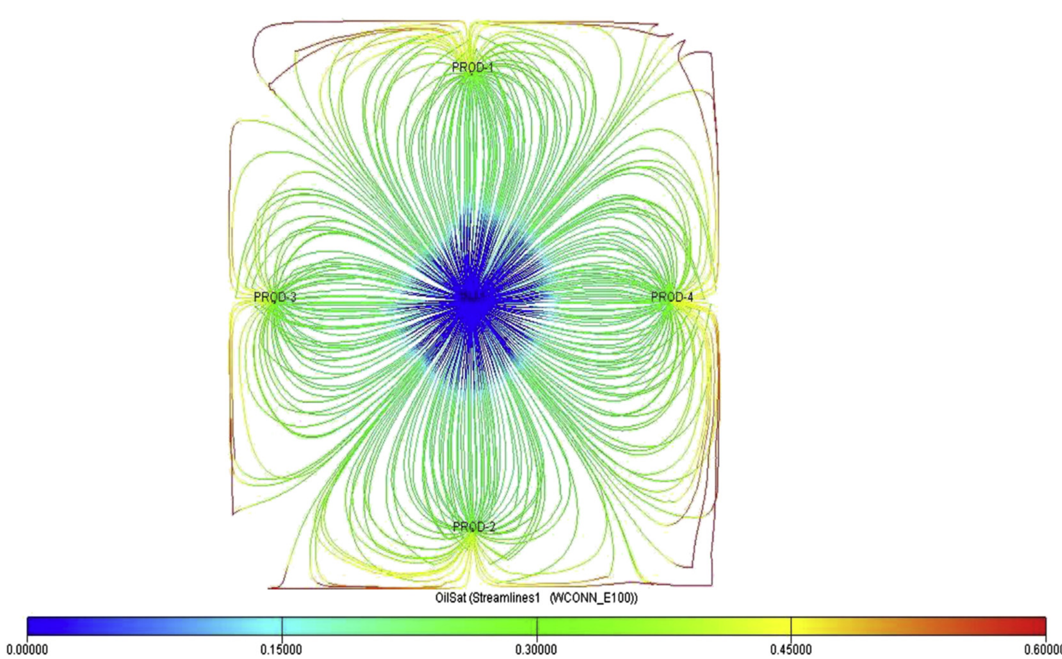

Fig. 4. Streamline distribution (500 d).

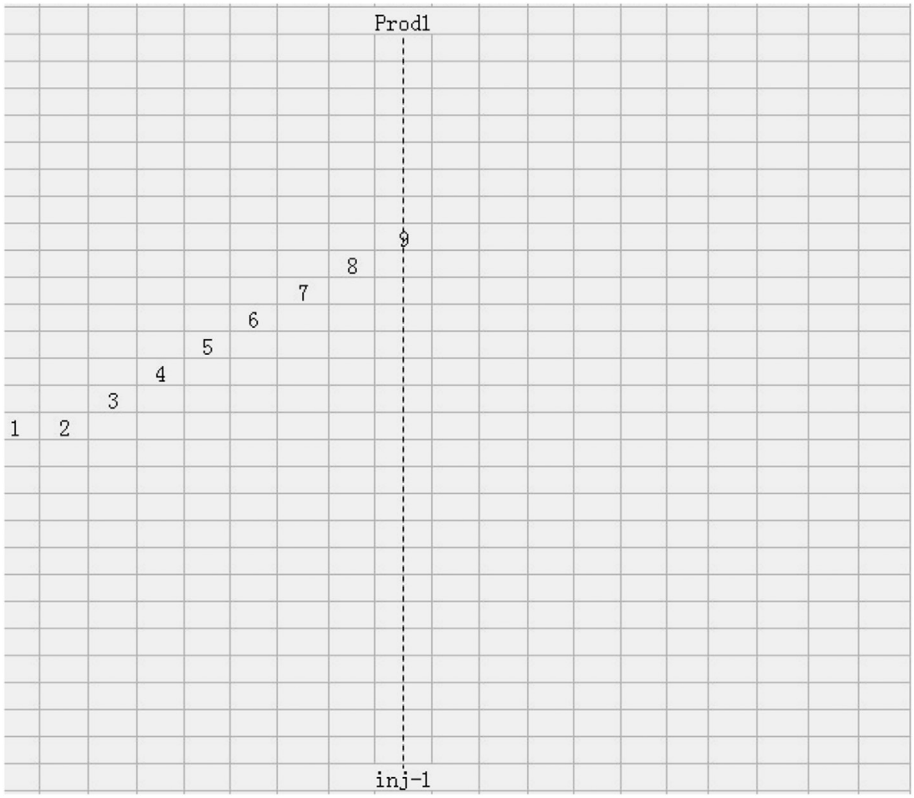

Fig. 5. Location of nine arbitrary grid blocks.

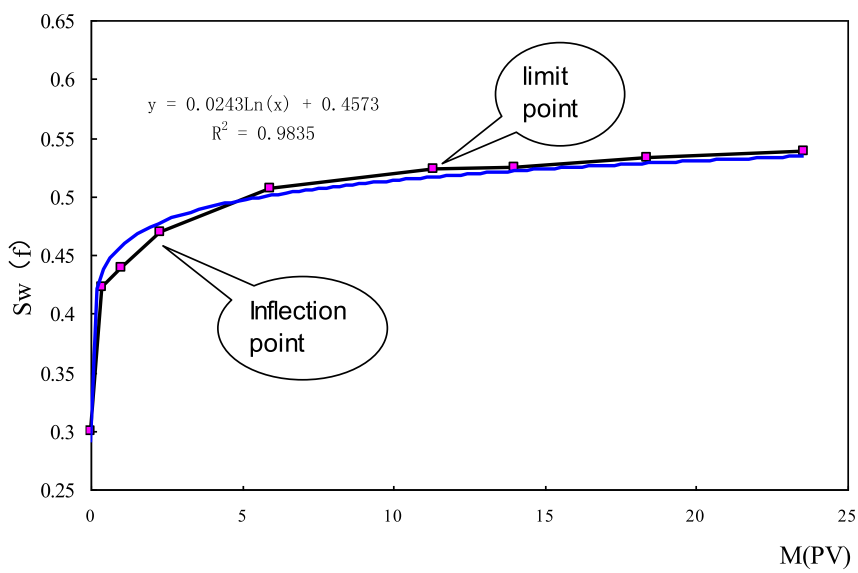

Fig. 6. Relationship between S_w and M in grid block P5.

Table 5
Regression parameters of nine grids.

Grid	A	B	Inflection point (PV)	Limit point (PV)
P1	0.03	0.4354	5.0	20
P2	0.0291	0.4455	4.5	15
P3	0.0309	0.4472	3.0	15
P4	0.024	0.456	3.5	15
P5	0.0243	0.4573	2.5	12
P6	0.0238	0.4531	4.5	19
P7	0.0274	0.4392	6.7	23
P8	0.0317	0.4354	6.5	25
P9	0.0362	0.4181	4.6	20

(2) The relationship between the cumulative water injection pore volume and water saturation is logarithmic relation, which is consistent to the existing experiment result.
(3) An inflection point and limit point exist in the relation between S_W and M,.which are useful to optimize water flooding process and facilitate key operation decisions.

Acknowledgments

This work was financially supported by the National Basic Research Program of China (973) Program, 'study on water injection in fracture-cave carbonate reservoir' (2011CB201000).

References

[1] Hequan Li, Zhaoliang Wu, Mingyuan Li, et al., Establishment of a practical water flooding model and its application to analysis of enhanced oil recovery efficiency, J. Univ. Pet. Ed. Nat. Sci. 26 (4) (August 2002) 51–52.
[2] Shuhong Ji, Changbing Tian, Chengfang Shi, et al., New understanding on water-oil displacement efficiency in a high water-cut stage, Pet. Explor. Dev. 39 (3) (June 2012) 338–344.
[3] Kaoping Song, Yushu Wu, Bingyu Ji, A φ-fanction method for estimating distribution of residual oil saturation in water drive reservoir, Acta Pet. Sin. 27 (3) (May 2006) 91–95.
[4] Hanbing Xu, Xiangfang Li, Depei Shi, et al., An analytical method for calculating water cut of producers in injection-production pattern, Acta Pet. Sin. 31 (3) (May 2010) 471–474.
[5] Jinyu Liu, Diansheng Wang, Bolin Liu, et al., Study on the variation law of the water-cut of low-permeability low-saturation sandstone reservoirs in water displacing oil, J. Xian Shiyou Univ. Nat. Ed. 26 (1) (Jan 2011) 37–41.

Feng Guo-qing (1974–), Male, Ph. D, Associated professor. E-mail address: drfenggq@163.com.

Yu Ming-Le (1987–), Male, M.D. E-mail address: 1030019049@qq.com.