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Study on Injection-Production System Adjustment of Fault Block Reservoir Based on Equilibrium Displacement

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Abstract

This paper proposed a method of injection-production system adjustment to solve the problem that the water flooding effect was restricted because of the horizontal and vertical contradictions during the development process of fault block reservoirs. Considering the heterogeneity of reservoir, the Buckley-Leverett water flooding theory was applied to establish the relationship between the recovery and cumulative water injection. In order to achieve the goal of vertically balanced recovery of each section, the calculation method of vertical sectional injection allocation was proposed. The planar triangular seepage unit was assumed and sweep coefficients of different oil-water distribution patterns were characterized using multi-flow tube method. In order to balance and maximize the plane sweep coefficient, the calculation method of plane production system optimization was obtained. Then the injection-production system stereoscopic adjustment method based on equilibrium displacement was proposed with vertical sectional injection allocation and plane production system optimization. This method was applied to injection and production adjustment of BZ oilfield in southern Bohai. The effect of water control and oil increase was obvious. This method can greatly improve the effect of water flooding of offshore fault block reservoirs with the adjustment of injection-production system.

Keywords

Fault Block Reservoir, Equilibrium Displacement, Vertical Sectional Injection Allocation, Planar Production System Optimization, Adjustment of Injection-Production System

1. Introduction

The complex fault-block reservoirs in the southern Bohai Sea are characterized by rapid changes in planar physical properties, multiple vertical layers, strong vertical and planar heterogeneity. Irregular well pattern with directional well is used to develop this type of reservoirs. Due to the influence of reservoir properties, fluid properties and well pattern, the vertical and horizontal contradictions always lead to the disequilibrium displacement in the water flooding development process of oilfields. And the disequilibrium displacement leads to the rapid increase of water cut and decline in production. Equilibrium displacement to development of reservoir can achieve maximum oil recovery and economic benefits. Separated layer injection adjustment and plane production system optimization are important ways to improve the effect of water flooding in reservoir development.

Many studies about separated layer injection adjustment and plane production system optimization have been carried on. For the separated layer injection adjustment, methods based on static parameters and field experiences are commonly used. WU Jiawen (2006) proposed an optimization method for layered water injection project based on the distribution of remaining oil [1]. Different strategies of water injection are established and fuzzy mathematics method is used to optimize the various injection schemes. SHI Xiaoqu (2008) studied a dynamic splitting equation considering static reservoir parameters and dynamic development data to establish the injection of separated layer [2]. CUI Chuanzhi (2017) proposed an rational sectional water injection allocation method based on equilibrium displacement [3]. He classified the layers according to the differential absorption index as the dividing standard. Based on Buckley-Leverett displacement theory, the method of calculating the water allocation of each section was established to achieve equilibrium displacement. But some of these methods are only suitable for middle and low water cut stage, some are difficult to obtain calculation parameters, and some do not really achieve the goal of internal equilibrium displacement. On the other hand, serval methods have been proposed to conduct production system optimization to realize plane equilibrium displacement. WANG Delong (2011) studied the effect of permeability range on well spacing and production, and established the optimum well spacing and production for heterogeneous reservoirs using numerical simulation method [4]. Aiming at the problem of injection-production imbalance in plane heterogeneous reservoirs, YAN Ke (2015) proposed a balanced water drive adjustment method based on multi-parameter quantitative calculation by using numerical simulation and reservoir engineering methods [5]. CUI Chuanzhi (2015) established a production optimization method in fault reservoir using non-pistion water flooding theory [6]. The method considered two factors of the reservoir physical properties heterogeneity and remaining oil saturation. WANG Xiang (2018) proposed the design formula of a well pattern for a heterogeneous reservoir to realize equilibrium displacement [7]. The heterogeneity of the reservoir and the non-piston displacement characteristics of the injected water were considered. The relationship between well spacing and reservoir dynamic and static parameters were derived. Their studies either only considered the displacement between injection and production wells, or were complicated to calculate.

J. I. Bingyu (2008) studied the method of oil production calculation for areal well pattern of low-permeability reservoir with non-Darcy seepage flow [8]. The multi-flow tube method (MTM) was firstly used in the calculation. And on this basis, GUO Fenzhuan (2010), ZHU Shengju (2013) and HE Congge (2015) all studied the calculation method of plane sweep coefficient for different well pattern in low-permeability reservoir [9] [10] [11]. But the application of production system optimization to realize plane equilibrium displacement with maxim sweep coefficient was not realized in their study.

On the basis of previous studies, using non-piston water flooding theory, this paper studies the calculation method of injection allocation for realizing balanced recovery of each section. Irregular well pattern is divided into different triangular injection-production seepage units in plane, and the optimization method of injection and production pressure difference is obtained by MTM to realize production system optimization. According to the calculation results of water injection allocation volume of each layer, separate injection of the injection wells are adjusted, and according to the calculation results of the plane injection production pressure difference, the oil nozzles or pump frequency of the production wells are adjusted, then injection and production system adjustment method based on balanced displacement is obtained by combining the two methods. The method has been applied in oil field, and the effect of oil stabilization and water control is achieved.

2. Injection-Production System Adjustment Theory

2.1. Method of Sectional Water Injection Calculation

The purpose of sectional water injection is to alleviate the contradiction between layers and reduce the interlayer interference caused by the difference of reservoir and fluid physical properties. By adjusting the injection volume of each section, the oil recovery of each section is consistent at a certain time, then the vertical balanced displacement is realized eventually. According to the degree of recovery at different time, the cumulative injection can be calculated, and the sectional injection is obtained under constant speed injection.

If injection water doesn't breakthrough in the jth section, according to Buckley-Leverett's non-piston water flooding theory [12], the accumulated water in section can be expressed as

$$W_j = \int_0^T Q_j \mathrm{d}t = x_{\mathrm{f}j} \phi A \big/ f'_{\mathrm{w}}\left(S_{\mathrm{wf}j}\right) \quad (1)$$

where W_j is the accumulated water injection in the jth section, T is the cumulative water injection time, Q_j is the water injection volume in section, t is the injection time, X_{fj} is the oil-water front position in the jth section, ϕ is reservoir porosity, A is the seepage section area, S_{wfj} is the water saturation of oil-water front in section, $f'_{\mathrm{w}}\left(S_{\mathrm{wf}j}\right)$ is the derivative of the water cut corresponding to the water saturation of oil-water front.

Under the condition that the amount of injection remains constant, the average injection volume can be obtained according to the following formula.

$$\bar{Q}_j = \phi A\left[L/f'_{\mathrm{w}}\left(S_{\mathrm{w}2j}\right) - x_{\mathrm{f}j}/f'_{\mathrm{w}}\left(S_{\mathrm{wf}j}\right)\right]/\Delta t \tag{2}$$

where $\bar{Q}_j$ is the allocation of water injection in the *j*th section, Δt is allocation of water injection time, L is the distance of injection to prodution, S_{w2j} is the water saturation at the outlet of the *j*th section after water breakthrough, $f'_{\mathrm{w}}\left(S_{\mathrm{w}2j}\right)$ is the water content derivative corresponding to water saturation at the outlet after water breakthrough. The allocation water injection rate cannot be solved directly, but can be obtained iteratively by setting the predicted outlet saturation.

Before water breakthrough, the recovery of reservoir in the jth section can be obtained by cumulative injection water:

$$R_j = W_j/(\phi AL) \tag{3}$$

After water breakthrough, the recovery of reservoir in the *j*th section can be obtained by average water saturation:

$$\begin{aligned} R_j &= \left(\bar{S}_{\mathrm{w}j} - S_{\mathrm{wi}}\right)/\left(1 - S_{\mathrm{wi}}\right) \\ &= \left\{S_{\mathrm{w}2j} + \left[1 - f_{\mathrm{w}}\left(S_{\mathrm{w}2j}\right)\right]/f'_{\mathrm{w}}\left(S_{\mathrm{w}2j}\right) - S_{\mathrm{wi}}\right\}/\left(1 - S_{\mathrm{wi}}\right) \end{aligned} \tag{4}$$

where R_j is the oil recovery factor, S_{wi} is the irreducible water saturation, $f_w(S_{w2j})$ is the outlet water content in the *j*th section.

If injection water has breakthrough in the *j*th section, the cumulative injection volume required for the water saturation from S_{wj} to S_{w2j} at the outlet of the *j*th section can be expressed as

$$\int_T^{T+\Delta t} Q_j \mathrm{d}t = L\phi A\left[1/f'_{\mathrm{w}}\left(S_{\mathrm{w}2j}\right) - 1/f'_{\mathrm{w}}\left(S_{\mathrm{w}j}\right)\right] \tag{5}$$

where S_{wj} is the outlet water saturation of the *j*th section before allocation, $f'_{\mathrm{w}}\left(S_{\mathrm{w}j}\right)$ is the water content derivative corresponding to water saturation at the outlet after water breakthrough.

Assuming that the injection allocation of each section remains constant in Δt time, the injection allocation of the *j*th section can be obtained by

$$\bar{Q}_j = L\phi A\left[1/f'_{\mathrm{w}}\left(S_{\mathrm{w}2j}\right) - 1/f'_{\mathrm{w}}\left(S_{\mathrm{w}j}\right)\right]/\Delta t \tag{6}$$

When this method is used to segmental injection allocation, the recovery factor of each section can be obtained according to the accumulated water volume of each layer. By setting allocation time and target recovery factor, the accumulated water volume of each segment is calculated, and then the injection allocation amount of each section can be obtained.

2.2. Method of Planar Production System Optimization

The injection-production well pattern is divided into different triangular seepage units (1/2 of the maximum area can be affected by water injection wells). The two vertices of the triangle seepage unit are water injection well and corresponding oil production well. The triangle seepage unit is assumed to be homogeneous and equal thickness reservoir. The oil and water well are composed of flow tubes. The seepage rule in the flow tubes conforms to the oil-water two-phase piston displacement. The compressibility of formation rocks and fluids, the capillary force and gravity are neglected, and the injection-production pressure difference is constant. As shown in **Figure 1**, each flow tube between injection and production well has only one turning point *O*. Geometric relation formula can be expressed as

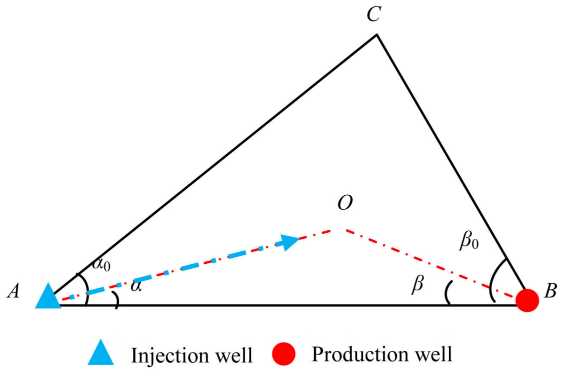

Figure 1. Flow tube diagram of injection-production seepage unit.

$$\alpha/\beta = \alpha_0/\beta_0 \tag{7}$$

where α is the angle between streamline AO and injection-production connection line, β is the angle between streamline BO and injection-production connection line, α_0 is the angle between sweep maximum area triangle side AC and injection-production connection line, β_0 is the angle between sweep maximum area triangle side BC and injection-production connection line.

In the case of oil and water two-phase flow, the length of the water phase displacement of any angle at any time t is [13]

$$\xi = \frac{C\left(p_{\text{inj}} - p_{\text{wf}}\right)}{\frac{\mu_o}{K_o} - \frac{\mu_w}{K_w}} \left\{ \frac{\frac{\mu_o}{K_o}\frac{L(\sin\alpha + \sin\beta)}{\sin(\alpha+\beta)}}{p_{\text{inj}} - p_{\text{wf}}} - \sqrt{\frac{-2\left(\frac{\mu_o}{K_o} - \frac{\mu_w}{K_w}\right)}{p_{\text{inj}} - p_{\text{wf}}} t + \left[\frac{\frac{\mu_o}{K_o}\frac{L(\sin\alpha + \sin\beta)}{\sin(\alpha+\beta)}}{p_{\text{inj}} - p_{\text{wf}}}\right]^2} \right\} \tag{8}$$

where C is a constant(C = 0.0864), p_{inj} is the bottom hole pressure of injection well, p_{wf} is the bottom hole flow pressure of production well, μ_o is the viscosity of reservoir crude oil, μ_w is formation water viscosity, K_o is the oil phase permeability, K_w is the water phase permeability.

According to the distribution of oil and water at different times, the whole displacement process can be divided into four periods: when t is less than T_1' (α = 0, the time when the oil-water front reaches the turning point O of AB), the oil-water fronts in flow tubes don't reach the turning point of the flow tube. When t is greater than T_1' and less than T_2' ($\alpha = 0$, the time when the oil-water front reaches point B), part of the oil-water fronts in flow tubes have reached the turning point, but not reached the production well. When t is greater than T_2'

and less than T_3' ($\alpha = \alpha_0$, the time of the oil-water front reaching *C* point), most of the oil-water fronts in flow tubes have crossed the turning point, and some of them reach the production well. When *t* is greater than T_3' and less than T_4' ($\alpha = \alpha_0$, the time of the oil-water front reaching *B* point), the oil-water fronts in flow tubes have crossed the turning point, and reached the production well.

The area sweep coefficient of triangular seepage unit is the ratio of sweep area to unit area, and the water content is the ratio of flow rate in flow tubes that the front of water drives to the well to all flow rate in flow tubes.

$$f_w = \sum_{j=1}^{n} Q_j \Big/ \sum_{i=1}^{m} Q_i \tag{9}$$

$$E_a = \sum_{i=1}^{n} S_i \Big/ S \tag{10}$$

where f_w is the water cut of production well, E_a is the area sweep coefficient, m is the total number of flow pipes, n is the number of flow pipes that the front of the water reaches the production well, Q_i, Q_j are the flow rates of the *i*th and *j*th flow pipe, S_i is the area of the *i*th flow pipe, S is the area of ΔABC.

The area sweep coefficient and water cut of production well are calculated by judging the distribution in each flow pipe at different time. Setting the target area sweep coefficient of the adjustment time, the injection-production pressure difference of the corresponding seepage unit is inversely calculated. Through the adjustment of production system optimization, the eventual balanced displacement can be achieved.

2.3. Adjustment Method of Injection-Production System

Based on the above theory, a method of injection-production system adjustment for offshore fault-block reservoirs is established. According to cumulative water injection and water content of each section vertically, the recovery degree and water saturation at the outlet can be obtained by Equation (1) or Equation (5). The target water saturation at the outlet end can be calculated by Equation (4) after setting the target recovery degree of each section. And the average injection allocation of each section in the target time is calculated according to Equation (2) and Equation (6). On the plane, injection-production triangle seepage units are divided. And fluid properties and well pattern parameters of each unit are obtained. According to the current water content of production well in the unit, the area sweep coefficient and the oil-water front distribution are derived. The area sweep coefficient of each seepage unit is compared, and the seepage unit with smaller plane area sweep coefficient needs to increasing injection-production pressure difference to improve water flooding effect. By setting the sweep coefficient of the target area of each seepage unit, the injection-production pressure difference is calculated according to Equation (8). The production system of production wells is adjusted according to injection-production pressure difference. Equilibrium displacement can be achieved through vertical and horizontal injection-production adjustment, thus the development effect of water flooding can be improved. The calculation procedure is shown in **Figure 2**.

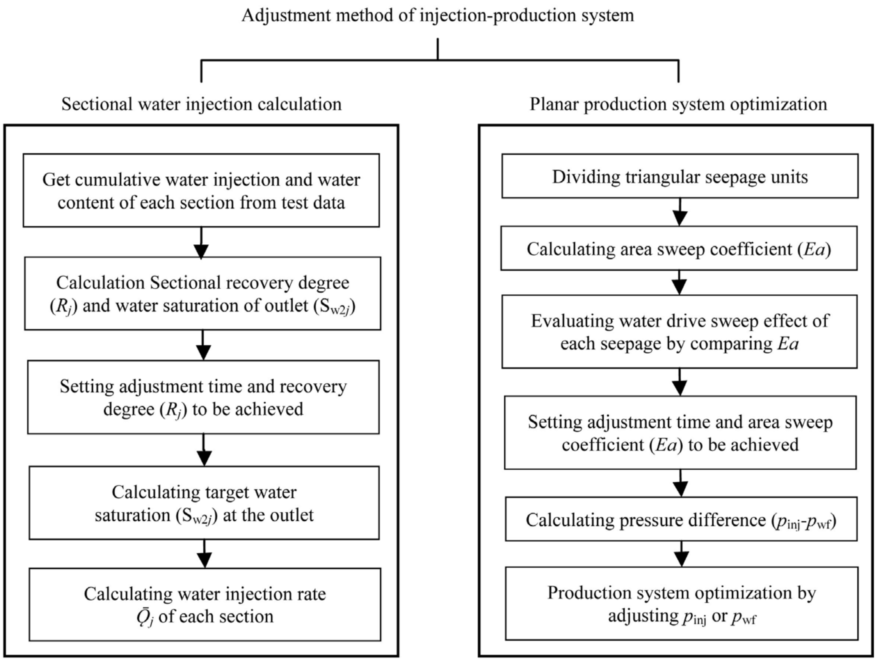

Figure 2. Flow chart of injection and production system adjustment.

3. Field Applications

The injection-production adjustment of S1 block in BZ oilfield has been conducted by using this method, as shown in **Figure 3**. The production layers of the block are N_1m^l I-1 layer and I-2 layer. The development mode of commingled production by directional production wells and sectional water injection by directional water injection wells. The injection and production system adjustment of well I1-P1 is shown in this paper. The well spacing from I1 well to P1 well and P2 well is respectively 590 m and 420 m, and the well spacing between P1 well and P2 well is 745 m. The reservoir and fluid parameters are shown in **Table 1**.

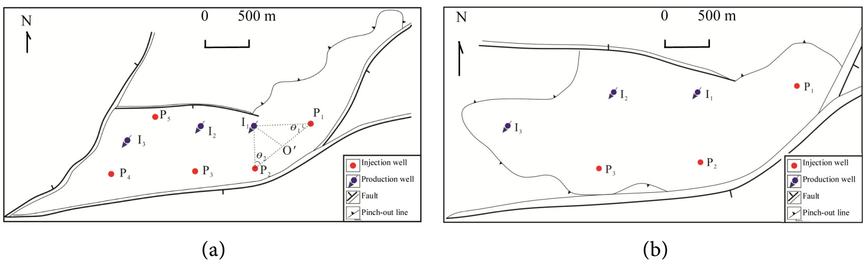

Figure 3. Development well pattern of S1 block in BZ oilfield. (a) I-1 layer of S1 block in BZ oilfield; (b) I-2 layer of S1 block in BZ oilfield.

Table 1. Reservoir and fluid parameter of S1 block in BZ oilfield.

Layer	Parameters				
	Thickness (m)	Porosity (%)	Permeability (mD)	Viscosity of formation water (mPa·s)	Viscosity of crude oil (mPa·s)
I-1	6.5	30.0	1051	0.1	12.9
I-2	8.1	32.0	1983	0.1	12.5

3.1. Vertically Sectional Injection Adjustment

The test results of production profile of well P1 before allocating shows the water cut in I-1 layer is 45.0% and the water content in I-2 layer is 60.8%. Calculated by Equation (5), the recovery factor of layer I-1 is 13.8%, the recovery factor in layer I-2 is 17.7%. The calculation result shows that due to good reservoir physical properties of I-2 layer, the injected water front advances rapidly along this layer. The recovery of layer I-1 is lower than that of layer I-2. Water injection allocation is needed to tap the remaining oil potential. The allocation time is set to 300 days, and the target recovery of the two layers is 20.0%. The average injection allocation of layer I-1 is 96 m^3/d and that of layer I-2 is 68 m^3/d, which is calculated by Equation (6).

3.2. Planar Production System Optimization

The well group is divided into two seepage units as shown in Figure 3. The angle θ_1 is 35 degrees, and the angle θ_2 is 53 degrees. The area sweep coefficient is calculated for each seepage unit respectively by applying this method. The area sweep coefficient of seepage unit (1) is 0.52. The area sweep coefficient of seepage unit (2) is 0.78. In order to achieve equilibrium displacement, the sweep area of seepage unit (1) needs to be increased. The target time is 300 days and the target area sweep coefficient is 0.80. The injection-production pressure difference in well I1-P1 direction is optimized. By increasing the production frequency of pump in well P1, the injection-production pressure difference is increased from 10.0 MPa to 11.7 MPa.

3.3. Application Result

After adjustment, the effect of water control and oil increase is obvious, as shown in Figure 4. The daily oil production increase 24 m^3, and the water cut remains stable. This method has been applied to adjust injection-production system of other well groups in this block, and the effect is remarkable. The daily oil increase is 110 m^3, and the annual production decline rate is only 1.5%, which improves the development effect of water flooding.

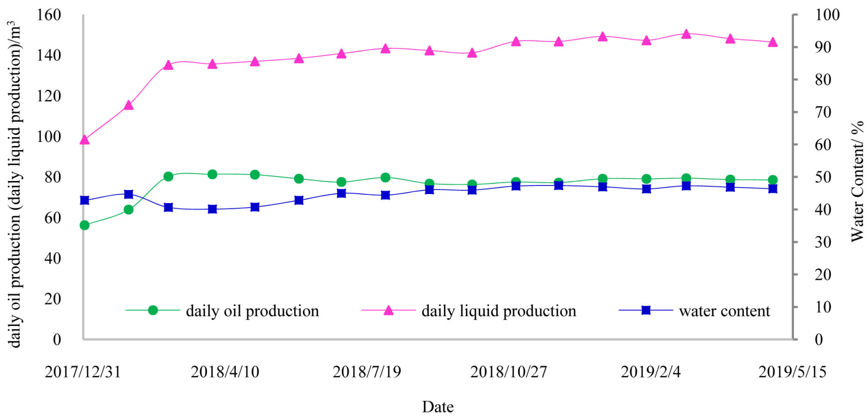

Figure 4. Well group production curve.

It should be figured out that absolute equilibrium displacement cannot be achieved due to the heterogeneity of actual reservoirs. In addition, the adjustment of injection-production system is a dynamic process. A relatively balanced displacement needs to be adjusted in time according to the development dynamics and combined with the corresponding technological measures.

4. Conclusions

1) Aiming at the prominent contradiction between layers in multi-layer development of offshore fault-block reservoirs, based on Buckely-Leverett non-piston water flooding theory, a sectional injection allocation method is established. By setting the unified target recovery of each section, the vertical balanced displacement can be achieved.

2) In order to maximize the plane sweep area of water flooding, injection-production well group is divided into triangle seepage units. By using multi-flow pipe method, the adjustment method of production system optimization for offshore fault-block reservoirs with irregular pattern development is established to realize horizontal balanced displacement.

3) Combining the vertical sectional injection allocation method and planar production system optimization method, the injection-production system adjustment method of fault block reservoir is established. This method is applied to guide the injection-production system adjustment in block S1 of BZ oilfield. The practical application results show that this method has obvious effect on water control and oil production increase. And the annual production decline rate of the S1 block is only 1.5%. This method has achieved good application effect, which can conduct the injection-production system adjustment of offshore fault block reservoirs.

4) It should be pointed out that the method of sectional water injection calculation proposed in this paper does not consider the influence of plane well pattern. Moreover, the hypothesis of triangular seepage unit division with planar production system optimization is limited to the reservoir with strong heterogeneity. Further study is needed to improve the above limitations.

Conflicts of Interest

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

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Nomenclature

W_j Accumulated water injection in the *j*th section, m^3
T Cumulative water injection time, d
Q_j Water injection volume in section, m^3
t Injection time, d
X_{fj} Oil-water front position in the *j*th section, m
ϕ Reservoir porosity, dimensionless
A Seepage section area, m^2
S_{wfj} Water saturation of oil-water front in section, m
$f'_w\left(S_{wfj}\right)$ Derivative of the water cut corresponding to the water saturation of oil-water front, dimensionless
$\bar{Q}_j$ Allocation of water injection in the *j*th section, m^3
Δt Allocation of water injection time, d
L Distance of injection to prodution, m
S_{w2j} Water saturation at the outlet of the jth section after water breakthrough, dimensionless
$f'_w\left(S_{w2j}\right)$ Water content derivative corresponding to water saturation at the outlet after water breakthrough, dimensionless
R Oil recovery factor, dimensionless
S_{wi} Irreducible water saturation, dimensionless
$f_w(S_{w2j})$ Outlet water content in the *j*th section, dimensionless
S_{wj} Outlet water saturation of the *j*th section before allocation, dimensionless
$f'_w\left(S_{wj}\right)$ Water content derivative corresponding to water saturation at the outlet after water breakthrough, dimensionless
p_{inj} Bottom hole pressure of injection well, MPa
p_{wf} Bottom hole flow pressure of production well, MPa
μ_o Viscosity of reservoir crude oil, mPa·s
μ_w Viscosity of formation water, mPa·s
K_o Oil phase permeability, dimensionless
K_w Water phase permeability, dimensionless
f_w Water cut of production well, dimensionless
m Total number of flow pipes, dimensionless
n Number of flow pipes that the front of the water reaches the production well, dimensionless
Q_i Flow rates of the *i*th flow pipe, dimensionless
E_a Area sweep coefficient, dimensionless
S Area of triangle seepage unit, m^2
S_i Area of the *i*th flow pipe, m^2

Subscripts

j Serial number of layer
i Serial number of flow tube
w water phase
o oil phase