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3D Physical Simulation of Water Flooding Characteristics of Buried Hill Reservoir with Different Fracture Systems

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Abstract

In order to understand the water-flooding characteristics of different fracture systems in metamorphic rock buried hill reservoirs and the mechanism of improving water-flooding development effect, a three-dimensional physical model of fractured reservoirs is established according to the similarity criterion based on the prototype of metamorphic buried hill reservoirs in JZ Oilfield in Bohai Bay Basin. Combined with the fractured reservoir characteristics of JZ Oilfield, the water displacement characteristics of the top-bottom staggered injection-production well pattern in different fracture network mode and different fracture development degree of buried hill reservoir are studied. The experimental results show that: 1) the more serious the fracture system irregularity is, the shorter the water-free oil production period is and the lower the water-free oil recovery is. After water breakthrough of production wells, the water cut rises faster, and the effect of water flooding development is worse; 2) under the condition of non-uniform fracture development, the development effect of the bottom fracture undeveloped is better than that of the middle fracture undeveloped. Water injection wells are deployed in areas with relatively few fractures, while oil wells are deployed in fractured areas with higher oil recovery and better development effect.

Keywords

Metamorphic Buried Hill Reservoir, Different Fracture Systems, 3D Physical Simulation, Water Flooding Characteristics

1. Introduction

In recent years, with the gradual deepening of petroleum exploration and development in China, a large number of fractured reservoirs have been found, and the proved reserves account for more than 1/4 of the total proved reserves. Among them, the metamorphic buried hill reservoir as an important part of the fractured reservoir, plays an important role in the stable production of oil industry [1]-[6]. Compared with conventional sandstone reservoirs, fractured reservoirs have the characteristics of complex geological structure, strong heterogeneity, complex oil and water seepage law, and difficult to control the rising rate of water cut after water breakthrough in oil wells, which make the development of this kind of reservoirs have great difficulties [7]-[12]. In recent years, in order to better simulate the water flooding of fractured reservoirs, considering the serious distortion of experimental results from conventional small-scale models and equivalent fracture models, Liu *et al.* [13] established a large-scale physical model of porous-fractured double porosity oil reservoir and carried out water flooding experiments; Tong Kaijun [14] established a three-dimensional large-scale physical experimental model and carried out the study of water displacement characteristics; Ge Lizhen [15] established a three-dimensional large-scale physical experimental model and carried out the study of enhanced oil recovery after water flooding. However, the previous research results are based on homogeneous fracture system, and the research on the characteristics of water drive oil under the development of different fracture systems is less. However, the actual reservoir fracture system is complex and heterogeneity is strong, so the existing research results cannot be more effective in guiding the development of the oilfield. In this paper, the injection-production well pattern in buried hill reservoir of JZ Oilfield is taken as physical prototype, and the large-scale three-dimensional physical model characterizing matrix-fracture combination is established according to the similarity criterion by using outcrop rock samples. The water flooding characteristics of top and bottom staggered injection-production well pattern in different fracture network mode and different fracture development degree in buried hill reservoir are studied.

2. Three Dimensional Physical Simulation Experiment

2.1. Establishment of Seepage Mathematical Model

2.1.1. Model Assumptions

1) The seepage model is dual porosity and single permeability; 2) gravity exists, which is considered as bottom water driving oil and gravity as resistance; 3) the reservoir spaces are mainly fractures, dissolved pore and microfractures. The dissolved pores and microfractures are included in the bedrock system, and the fractures constitute the fracture system. The bedrock system supplies oil to the fracture system through capillary force, and the fracture system is the seepage channel; 4) the capillary force is neglected in fracture system; 5) oil and water are immiscible; 6) the fluid is incompressible and the percolation medium is slightly compressible; 7) in the model, there are one injection well and two production wells, the well type is horizontal well, the injection volume is constant q, the production well is produced at fixed bottom hole pressure, the horizontal well is

very small relative to the whole reservoir, and it can be used as "point source" or "point sink" when the whole reservoir is considered. The coordinates of the well location are taken as the middle point of the horizontal section; 8) the imbibition time is the same as the displacement time, that is, imbibition occurs in the bedrock at the beginning of displacement.

2.1.2. Seepage Mathematical Equation

Let the shape of the reservoir be a cuboid with length L_x, width L_y and height L_z. The location of the bottom water injection well (x_i, y_i, z_i) and the location of the top two production wells (x_{p1}, y_{p1}, z_{p1}) and (x_{p2}, y_{p2}, z_{p2}) are treated as source and sink terms. According to the assumption of the model, the bedrock system is regarded as the "source", and the seepage process mainly occurs in the fracture system. Therefore, taking the fracture system as the target, the seepage mathematical equation is established.

The continuity equation is as follows:

Oil phase:

$$\nabla \cdot \left[\frac{K_f K_{ro}}{\mu_o} \nabla \left(p - \gamma_o z \right) \right] - Q_o + F_o = \frac{\partial}{\partial t} \left(\varphi_f \cdot S_{of} \right) \tag{1}$$

Water phase:

$$\nabla \cdot \left[\frac{K_f K_{rw}}{\mu_w} \nabla \left(p - \gamma_w z \right) \right] - Q_w + F_w = \frac{\partial}{\partial t} \left(\varphi_f \cdot S_{wf} \right) \tag{2}$$

Q_o and Q_w are the point source and sink terms of the well. For the convenience of expression, the Dirac function is introduced:

$$\delta(x-c) = \begin{cases} 1 & x = c \\ 0 & x \neq c \end{cases}$$

Note that the Water injection volume of injection well is Q_{iw}, the water production of production well is Q_{pw1} and Q_{pw2} respectively, and the oil production is Q_{po1} and Q_{po2}, then the source-sink term can be expressed as:

$$Q_o = \sum_{j=1}^{2} Q_{poj} \delta\left(x - x_{pj}\right) \delta\left(y - y_{pj}\right) \delta\left(z - z_{pj}\right) \tag{3}$$

$$\begin{aligned} Q_w = {} & Q_{iw} \delta\left(x - x_i\right) \delta\left(y - y_i\right) \delta\left(z - z_i\right) \\ & - \sum_{j=1}^{2} Q_{pwj} \delta\left(x - x_{pj}\right) \delta\left(y - y_{pj}\right) \delta\left(z - z_{pj}\right) \end{aligned} \tag{4}$$

F_o denotes the amount of oil supplied to the fracture by imbibition of the matrix, and F_w denotes the amount of water displaced from the fracture into the matrix. Then:

$$F_o + F_w = 0 \tag{5}$$

The parameters related to the imbibition amount F_o include the imbibition time t_i, the half-life T, the imbibition coefficient D and the amount of oil that can be exuded from a unit volume of rock. F_o can be written as:

$$F_o = F_o\left(t_i, D, T, R\right) \tag{6}$$

Equation of state:

$$\varphi_f = \varphi_{f0}\left[1 + C_{\varphi f}\left(p - p_i\right)\right] \tag{7}$$

Auxiliary equation:

$$S_{of} + S_{wf} = 1 \tag{8}$$

Initial conditions:

$$p\big|_{t=0} = p_i \tag{9}$$

$$S_o\big|_{t=0} = S_{oi} \tag{10}$$

Outer boundary conditions (closed boundary):

$$\frac{\partial p}{\partial n} = 0 \tag{11}$$

2.2. Establishment of Similarity Criterion

Based on the mathematical percolation mechanism of double porosity and single permeability and the basic principles of geometric similarity, dynamic similarity and motion similarity, we establish the mathematical model of cuboid fractured reservoir under the condition of horizontal well displacement, the similarity criteria group of three-dimensional physical model of fractured reservoir is obtained by using dimensional analysis and equation analysis [16].

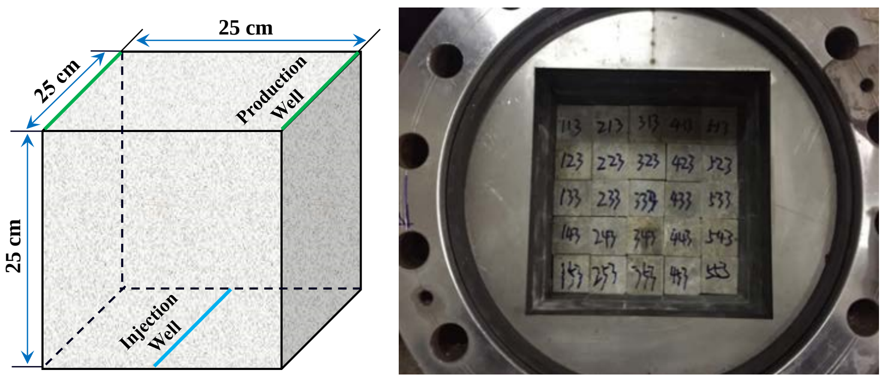
2.3. Model Making

In the actual fractured reservoir, the properties and distribution of fractures are very complex. In order to research conveniently, the classic Warren-Root model is used to simplify the fractures into mutually perpendicular fracture system and rock blocks are cut by the fracture system in the design of the actual model. According to the similarity criteria group, combined with the actual data of the scene, the cubic rock block with side length of 5 cm is selected, and a three-dimensional physical model with size of 25 cm × 25 cm × 25 cm is constructed combining with the actual field situation. According to the similarity criterion group in **Table 1**, the transformation between the field prototype and the laboratory physical model is obtained.

According to the reservoir petrophysical properties of fractured reservoir in JZ Oilfield, the shallow brown reticulated granite with abundant micro-fractures is selected as the displacement medium for the experiment. The average porosity of the rock is 4% - 7%, and the permeability is 0.3 - 1 mD, which is close to the actual situation of the field. According to the actual situation of the field, horizontal well is selected as the injection and production well type. The injection and production unit with one horizontal well at the bottom and two horizontal wells at the top two corners is used for physical simulation experiment (**Figure 1**).

Table 1. Similarity criterion of physical simulation.

Classification of similarity criteria	Number of similarity criteria	Physical significance
Geometric similarity	x/L_x, y/L_y, z/L_z	Ratio of dimensionless coordinates to feature length
	L_x/L_y, L_x/L_z	Ratio of appearance sizes in different directions
	L/L_x	Ratio of horizontal section length to reservoir length
	L/d	Ratio of horizontal section length to well spacing
	L_z/r_w	Ratio of reservoir thickness to well diameter
Motion similarity	$\dfrac{Dt\sqrt{K/\varphi_{fo}}\sigma t}{L_x L_y \left(1-\varphi_{fo}\right) R\mu_w L_x}$	Product of proportion of osmotic capacity in total reservoir permeable absorption and characteristic time
Dynamic similarity	$\left(1/C_f-\left(\gamma_w-\gamma_o\right)L_z\right)L_x K/q\mu_w$	Ratio of displacement power to pressure difference of injection and production
	μ_o/μ_w	Oil-water viscosity ratio
	$\left(p-p_i\right)L_x K/q\mu_w$	Ratio of pressure drop to pressure difference of injection and production



(a) (b)

Figure 1. Model design and equipment rendering. (a) Schematic diagram of top-bottom interlaced 3D injection-production well deployment model concerning the horizontal well; (b) Three dimensional physical model experiment equipment.

2.4. Physical Model Similarity Verification

In order to verify the accuracy of the similarity, the reservoir prototype and physical model values were calculated using Eclipse software, the relationship between the water cut, oil production and liquid production of the reservoir prototype and physical model over time can be obtained. By comparing the production characteristics of different production parameters, the similarity between the prototype and the model can be verified. It can be seen from the water cut curve of the two (Figure 2). The similarity between the calculation results of the reservoir prototype and the physical model is good, indicating that the physical model can meet the experimental requirements.

2.5. Experimental Scheme

Experiment 1: the characteristics of water flooding in different fracture network modes and its influence on development effect. According to the purpose of the experiment, two groups of experiments were designed. The first group of fracture systems is regular fractures in horizontal and vertical directions, as shown in Figure 1, a total of 1255 cm × 5 cm × 5 cm rock blocks are required to be combined into a three-dimensional model. The comparative experiment uses a fracture system with irregular developed fractures. As shown in Figure 3, it can be seen that the fracture development of each layer is irregular, and there are randomness and uncertainty in the fracture development of each layer, which can simulate the irregularity and uncertainty of complex fracture system well. At the same displacement speed, 1.1 mL/min is used for displacement in the two groups of experiments, and water displacement experiments are carried out in different fracture systems respectively, and the water cut rising law is compared.

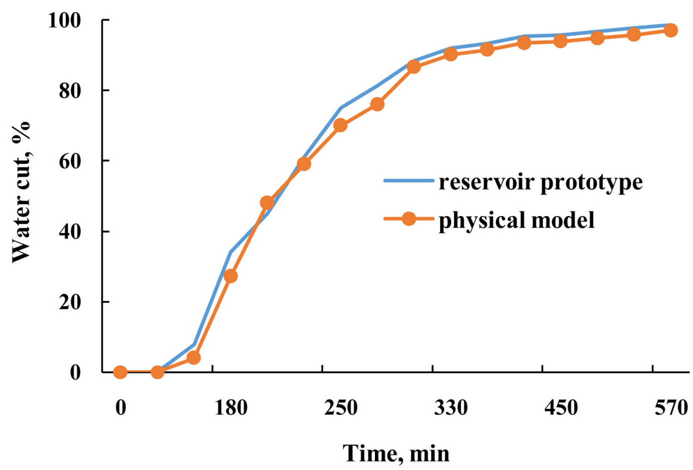


Figure 2. Comparison of water cut between reservoir prototype and physical model.

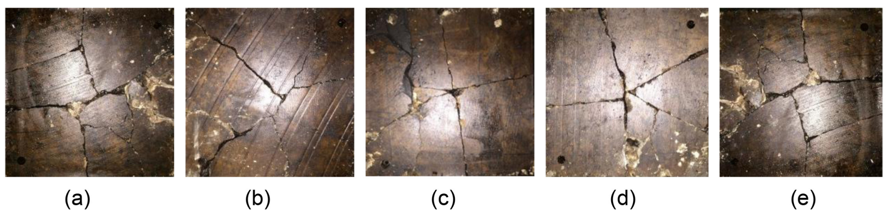


Figure 3. Distribution map of irregular fracture system. (a) 1st layer; (b) 2nd layer; (c) 3rd layer; (d) 4th layer; (e) 5th layer.

see Table 2 for specific experimental parameters.

Experiment 2: Study of the water drive characteristics of top-bottom interlaced injection production well pattern under different fracture development degree and its influence on development effect. According to the purpose of the experiment, two groups of experiments were designed. One group is that the bottom fracture is not developed and the top fracture is developed, that is, the top oil well is arranged in the fracture developed area, and the bottom water injection well is arranged in the fracture undeveloped area. The contrast experiment shows that the middle fracture is not developed, the top and bottom fractures are developed, that is, the fracture system is developed in the well deployment area which include the top oil well and the bottom water injection well, and the fracture in the middle area which between the oil well and the water injection well is not developed. As shown in Figures 4-6 is the dual medium model with different fracture development degrees, the fracture development area is composed of 5 cm × 5 cm × 5 cm rock blocks, and the fracture undeveloped area uses 10 cm × 10 cm × 10 cm rock blocks. The same displacement speed 1.1 mL/min is used for displacement in the two groups of experiments, and water displacement experiments are carried out under different fracture development degrees, and the water cut rising law is compared. See Table 2 for detailed experimental parameters.

3. Experiment Results and Analysis

3.1. Comparison of Water Flooding Characteristics in Different Fracture Modes

In the experiment of regular fracture system, the saturated oil of rock block is

Table 2. Basic parameters and experimental data of simulation experiment model.

Model number	Content		Saturated oil volume of rock block/mL	Saturated oil volume of fracture/mL	Total saturated oil volume/mL	reserves ratio of fracture to matrix	Oil production of rock block/mL	Oil production of fracture/mL	Total oil production/mL	Final recovery/%
	Purpose	Condition								
1	Comparison of water flooding characteristics in different fracture network models	Regular fracture system	417	233	650	1:1.8	38	150	188	28.9
2		Irregular fracture system	417	261	678	1:1.6	27	115	157	20.9
3	Comparison of water and oil displacement characteristics of top-bottom interlaced injection production well pattern under different fracture development degree	Non developed fracture in the bottom	421	175	596	1:2.4	34	81	115	19.3
4		Non developed fracture in the middle part	421	187	608	1:2.3	33	73	106	17.4

Figure 4. Photos of different rock blocks. (a) 5 cm × 5 cm × 5 cm rock block; (b) 10 cm × 10 cm × 10 cm rock block.

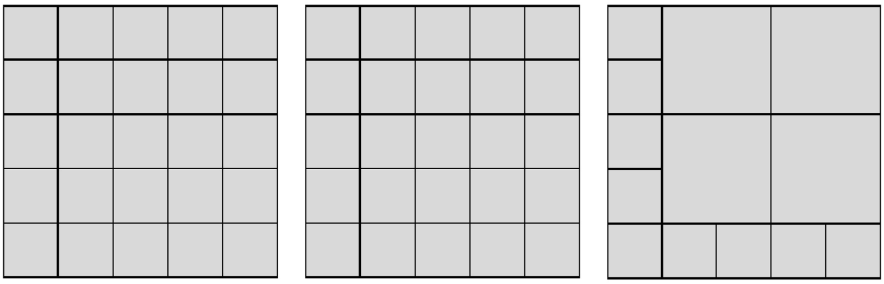


Figure 5. Schematic diagram of rock block combination with undeveloped fractures in the bottom. (a) Top combination of rock blocks; (b) Middle combination of rock blocks; (c) Bottom combination of rock blocks.

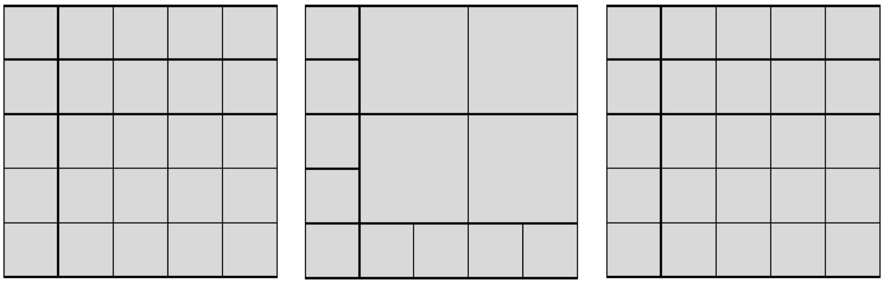


Figure 6. Schematic diagram of rock block combination with undeveloped fractures in the middle part. (a) Top combination of rock blocks; (b) Middle combination of rock blocks; (c) Bottom combination of rock blocks.

417 mL, the saturated oil of fracture is 233 mL, and the total oil content of model is 650 mL. The reserve ratio of fracture and matrix is 1:1.8. The water flooding time is 500 min, the water-free recovery of conventional water flooding is 16.2%, and the ultimate recovery is 28.9% (Figure 7 and Table 2), the recovery of matrix is 9.0%, the cumulative oil production is 38 mL, the recovery of fracture is about 64.4%, and the cumulative oil production is 150 mL. In the experiment of irregular fracture system, the saturated oil of rock block is 417 mL, the saturated oil of fracture is 261 mL, and the total oil content of model is 678 mL. The reserve ratio of fracture and matrix is 1:1.6. The water-free recovery of conventional

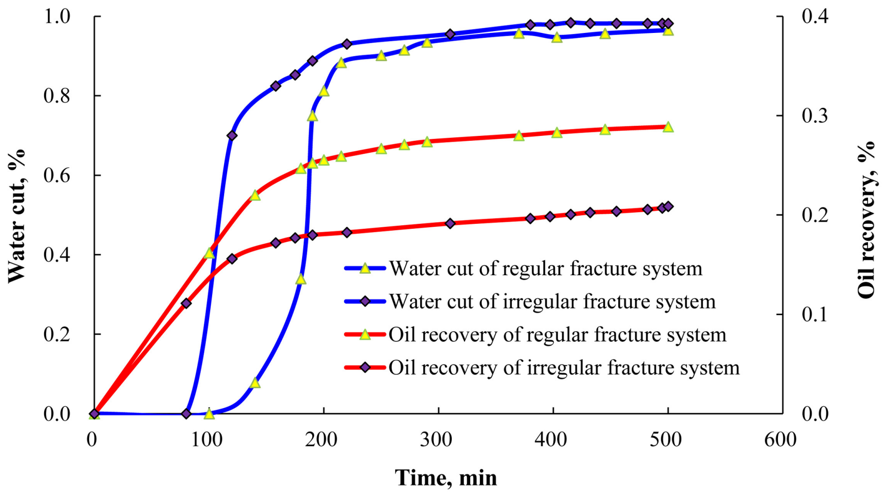


Figure 7. Relationship of water cut, oil recovery and time under different fracture system.

water flooding is 11.1%, and the ultimate recovery is 20.9% (**Figure 7** and **Table 2**), the recovery of matrix is 6.5%, the cumulative oil production is 27 mL, the recovery of fracture is about 43.9%, and the cumulative oil production is 115 mL.

Through two groups of experiments, it can be found that for the dual medium reservoir of buried hill metamorphic rock, the development process can be divided into three stages, that because the fracture permeability is far greater than the matrix permeability:

1) Water-free recovery stage: oil mainly produced by fracture system and very little produced by matrix system, and that leading to low oil recovery in water-free stage;

2) Rapid rising stage of water cut: when the production well break though, because the viscosity of water is less than that of oil, the water flow channel has stronger conductivity, The flow of water phase is very large, and the water cut of production well rises very fast, which is consistent with the actual production performance of fractured reservoir;

3) Slow rising stage of water cut: after the rapid rising stage of water cut, it enters into the slow rising stage of water cut. In this stage, because the producible crude oil reserves of the fracture system have been basically displaced, the water channeling channel has been formed stably, the contact area between matrix system and water has increased, and the oil displacement speed of imbibition is accelerated, in this stage, the fractured reservoir mainly produces oil through the imbibition of matrix system. In the fracture system, the saturation of oil phase is low, and the water cut is always at a high level.

Compared with regular fracture system, irregular fracture system has shorter water-free production stage, faster water cut rising stage and shorter water cut rising stage. The oil recovery of irregular fracture system is 11.1%, 5.1% lower than that of regular fracture system. After water breakthrough, the water cut rises to 70% quickly. At the same time, the slow water cut rise stage is shorter and the water cut rise is faster. This is because, for irregular fractures system, the fracture development is uneven, when injected water is flooding, it is easier to form dominant water channeling along the direction of large fractures with small resistance, once the water channeling channel is formed, the oil-water interface rises in a cone shape, and most injected water is produced along the water channeling channel, resulting in almost vertical rise of water cut. After the rapid rise of water cut, a small part of injected water can still slowly enter into the small and medium fractures. At this time, the water cut rises slowly, and the small and medium fractures will gradually water channeling, resulting in the water cut rising faster than regular fractures system. Due to the rapid rise of water cut in irregular fracture system, some crude oil with medium and small fractures is detained, which reduces the sweep efficiency of water flooding in the whole reservoir. Although the reserves of fractures in irregular fracture system are higher, the water-free recovery and final recovery are lower than those in regular fracture system.

3.2. Comparison of Water Flooding Characteristics of Well Pattern with Different Fracture Development Degree

In the experiment of bottom fracture undeveloped, the saturated oil of rock block is 421 mL, the saturated oil of fracture is 175 mL, and the total oil content of model is 596 mL. The reserve ratio of fracture and matrix is 1:2.4. Considering that the size of some matrix rocks increases and the water flooding time is 11 h, the water-free recovery of conventional water flooding is 12.2%, and the ultimate recovery is 19.3% (Figure 8 and Table 2), the recovery of matrix is 8.0%, the cumulative oil production is 34 mL, the recovery of fracture is about 46.5%, and the cumulative oil production is 81 mL. In the experiment of middle fracture undeveloped, the saturated oil of rock block is 421 mL, the saturated oil of fracture is 187 mL, and the total oil content of model is 608 mL. The reserve ratio of

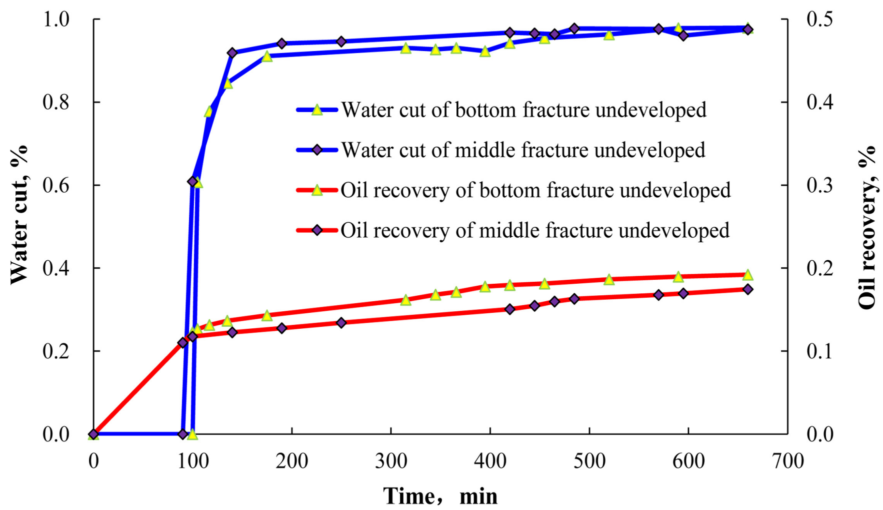


Figure 8. Relationship of water cut, oil recovery and time under different fracture development location.

fracture and matrix is 1:2.3. The water flooding time is 11 h, the water-free recovery of conventional water flooding is 11.0%, and the ultimate recovery is 17.4% (**Figure 8** and **Table 2**), the recovery of matrix is 7.8%, the cumulative oil production is 33 mL, the recovery of fracture is about 39.0%, and the cumulative oil production is 73 mL.

Through two groups of experiments, it can be found that under the condition of non-uniform fracture development, water-free recovery and ultimate recovery still show similar characteristics to those under the condition of homogeneous fracture. However, compared with the uniformly distributed fractures, the water cut rises faster under the non-uniform condition. When the fractures around the injection well are less developed, that is to say, when the bottom fractures are not developed, the middle and high water cut period is maintained for a period of time. When the fractures in the middle and bottom of the reservoir are not developed, although the ratio of fracture and matrix is slightly increased, the recovery of water-free and ultimate recovery are decreased to a certain extent. The main reason is that when the injection well is located at the bottom fracture development position, the injected water will soon reach the middle fracture after entering the fracture, resulting in a large number of crude oil in the bottom fracture being detained, the sweep coefficient of crude oil will be reduced, and ultimate recovery will be low (**Figure 9**). According to the above experiments, injection wells are arranged in areas with relatively few fractures, and production wells are arranged in areas with fracture development with higher ultimate recovery and better development effect.

4. Conclusions

1) Taking buried hill reservoir of JZ Oilfield in Bohai Sea as an example, a new large-scale three-dimensional physical simulation experiment is designed to

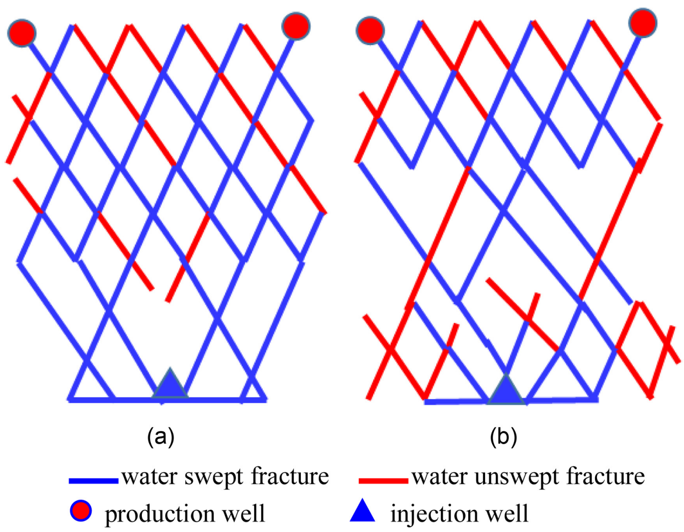


Figure 9. Different fracture development location. (a) Bottom fracture undeveloped; (b) Middle fracture undeveloped.

characterize matrix pore fracture combination according to fracture reservoir similarity criteria. The experimental results are representative and convincing.

2) The dynamic development characteristics of water flooding and the law of water cut rise are different under different fracture systems. The more irregular the fracture system is, the shorter the water-free recovery period and the smaller the water-free oil recovery. After the production wells breakthrough, the water cut rises faster and the development effect of water flooding is worse.

3) Under the condition of uneven fracture development, the development effect of undeveloped bottom fracture is better than that of undeveloped middle fracture. Injection wells are arranged in areas with relatively few fractures, and production wells are arranged in areas with fracture development, with higher ultimate recovery and better development effect.

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Conflicts of Interest

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

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