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Imbibition oil recovery of single fracture-controlled matrix unit: Model construction and numerical simulation

Qiang Liu[1], Bing Liang[1]*, Jianjun Liu[2]*, Weiji Sun[1], Yun Lei[3]

[1] *School of Mechanics and Engineering, Liaoning Technical University, Fuxin 123000, P. R. China*

[2] *State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, P. R. China*

[3] *State Key Laboratory of Coal Mine Safety Technology, Shenyang Research Institute, China Coal Technology & Engineering Group Corp., Fushun 113122, P. R. China*

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Abstract:
The fracture-controlled matrix unit is commonly found in low-permeability fractured reservoirs. Due to the permeability difference between the fracture system and the matrix system, a large amount of oil will remain in the matrix during traditional water injection development, thus limiting reservoir productivity. However, the special imbibition mode of the fracture-controlled matrix unit provides a breakthrough for secondary oil recovery. In this paper, based on the model of single fracture-controlled matrix unit, the dynamic production process of fractured reservoir is studied by the numerical simulation method. The numerical simulation of the imbibition oil production is carried out on the two-point well model by using the method of huff and puff injection. The results show that imbibition is the main mechanism in the middle and late stages of oil recovery from fractured reservoirs. The water in the fracture is absorbed into the matrix by capillary force and the oil is replaced; in this way, imbibition can increase the recovery rate by 20%. The findings provide a basis for the further study of the fracture-controlled matrix unit and imbibition.

1. Introduction

The extraction of residual oil from fractured reservoirs is an important procedure to enhance the efficiency of oil exploitation. In the early stages of reservoir development, a large amount of crude oil will remain in the matrix after traditional depletion (Abbasi et al., 2016). The long-term conventional water injection recovery development process makes a substantial proportion of low-permeability fractured reservoirs enter the middle and late stages. As a result, the water cut in the well increases rapidly (Meleán et al., 2003; Xiao et al., 2018; Alinejad and Dehghanpour, 2021). The effect of enhanced oil recovery through the single water injection method becomes gradually less obvious, and the difficulty of oil availability subsequently increases. More than 20% of the remaining oil resources are distributed in low-permeability reservoirs. Therefore, oilfield production will be limited, which directly affects the economic benefits. Accordingly, the further effective development of low-permeability fractured reservoirs has become an urgent technical problem to be addressed.

Meanwhile, the special fracture-controlled matrix unit system (matrix-fracture system (Chen et al., 2019)) brought about by low-permeability fractured reservoirs has proved to be a breakthrough (Cai et al., 2013, 2021; Sedaghat et al., 2017; Liu et al., 2020a, 2020b; Diao et al., 2021). Researchers have subsequently carried out a lot of work on imbibition oil recovery (Meng et al., 2008; Mohammadi et al., 2019; Tagavifar et al., 2019; Ghasemi et al., 2020). Moore and Slobod (1956) and Graham and Richardson (1959) studied the driving forces of the imbibition process through simple

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*Corresponding author.
E-mail address: liuqiang@lntu.edu.cn (Q. Liu); lbwqx@163.com (B. Liang); jjliu@whrsm.ac.cn (J. Liu); sunweiji-1231@163.com (W. Sun); leiyun_123@163.com (Y. Lei).

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imbibition experiments, and proposed that the main driving forces of imbibition were capillary force and gravity. The initial research trail was limited to the basic understanding of the imbibition oil production process. Babadagli and Boluk (2005) studied the influence of rock wettability on imbibition, and found that the imbibition efficiency could be greatly improved by changing the wettability using surfactants. However, qualitative research on the process and mechanism of imbibition could only be conducted by traditional experiments. Along with the development of multidisciplinary and cross-researches, more and more advanced technology such as nuclear magnetic resonance (NMR) and Computed Tomography was applied to core analysis (Berga et al., 2016; Mirzaei et al., 2016; Song et al., 2019; Liu et al., 2020c; Khosravi et al., 2021), making the development of imbibition leap from qualitative and semi-quantitative to three-dimensional visualization and quantification. It is worth mentioning that the fracture-controlled matrix unit core for imbibition experimental studies is difficult to obtain, even though its reconstruction method is critical for imbibition studies. Santos et al. (2017) proposed a core reconstruction method and the square or coin-shaped voids that could be used to characterize the fractures. With the development of digital core, laser engraving and 3D printing technology have been widely used in core reconstruction. The advantage of these methods is that the pore structure and fracture network inside the core can be modeled, so as to more accurately reflect the internal structure of the actual core. However, these methods also have disadvantages. First, the matrix material is made of sand, kaolinite, sodium silicate, or cement, which not only changes the physical properties of the matrix surface, but also fails to match the composition of real rocks. Second, chemical solvents such as acids react chemically with substances in the matrix, causing serious damage to the core. In terms of the characterization and establishment of two-dimensional imbibition numerical models, researchers have used various methods to fill the circular particles representing the matrix skeleton into the matrix, where the voids between the particles represented the pore structure in the matrix. Initially, the homogeneous two-dimensional porous media model was formed by filling round particles of equal size into the matrix uniformly and orderly (Akhlaghi Amiri et al., 2013), and fluids flowed in the same pore channels (Fichot et al., 2007).

In recent years, the numerical simulation of imbibition oil recovery by software was widely performed. Wang et al. (2019) realized the numerical simulation of static and dynamic imbibition considering capillary force and gravity, and used this model to study the influence of oil viscosity, matrix permeability, core size, surface tension, and displacement rate on imbibition. To improve the accuracy and stability of the imbibition simulation process, Zheng et al. (2018) proposed an improved the Boltzmann method to study the influence of irregular pore channel curvature on the imbibition behavior and competitive interface advancing behavior of bifurcated channels. The complex pore space of the matrix was simplified into a spatial-self-similar branching structure by Shen et al. (2017), the imbibition process was calculated, and the effects of pore structure and fluid characteristics on imbibition were discussed. Based on the compatibility equation algorithm and boundary integral theory, Bagherinezhad and Pishvaie (2014) developed a new two-dimensional green element method to simulate the counter-current imbibition process by the finite element method. A streamline simulation of counter-current imbibition in naturally fractured reservoirs was conducted by Al-Huthali and Datta-Gupta (2004), and this method showed good consistency with the numerical dispersion method in terms of history matching. The Adomian decomposition method was applied for one-dimensional and two-dimensional counter-current imbibition simulations performed by Behbahani et al. (2006) and Patel and Meher (2018) to analyze the dimensionless time reservoir recovery factor under the influence of gravity and tilt effect. However, the numerical simulation research on imbibition in porous rock media has mainly focused on small models to analyze the imbibition process and the distribution characteristics of oil and water, while the numerical model construction and numerical simulation of the reservoir scale fracture-controlled matrix unit still requires some basic research work.

This paper focuses on the study of a single fracture-controlled matrix unit, involving model construction and imbibition numerical simulation at the reservoir scale. A single fracture and homogeneous sandstone are used to characterize the fracture system and the matrix system, respectively, and the numerical model of fracture-controlled matrix unit is established at the reservoir scale. The fluid model is configured combined with field data. Then, the dynamic production process of fractured reservoir is studied. The results reveal that imbibition is the main oil recovery mechanism in the middle and late stages of fractured reservoir. This work provides a basis for the subsequent numerical simulation of imbibition oil production and multi-scale imbibition with heterogeneous fracture-controlled matrix units, including complex fractures at the reservoir scale.

2. Single fracture-controlled matrix unit numerical model

2.1 Fracture-controlled matrix unit

In low-permeability fractured reservoirs, the effect of imbibition to improve oil recovery has been recognized by researchers and field engineers alike. The imbibition mechanism and the imbibition recovery rate have been investigated by experiments, mathematical models and numerical simulations. These studies were all carried out on the matrix-fracture system (fracture-controlled matrix unit), therefore, the carrier on which the imbibition process relies on is highly important.

In our previous studies (Liu et al., 2020d), the fracture-controlled matrix unit had been clearly defined. The matrix system of the fracture-controlled matrix unit is the main storage space for crude oil, and fracture is the main site where imbibition occurs and is the main channel for fluid transportation. Therefore, the concept of fracture-controlled matrix unit can characterize the location/carrier where the imbibition process takes place. The occurrence of the imbibition process requires two systems-a fracture system and a matrix system, and the unit consisting of these two systems is called the

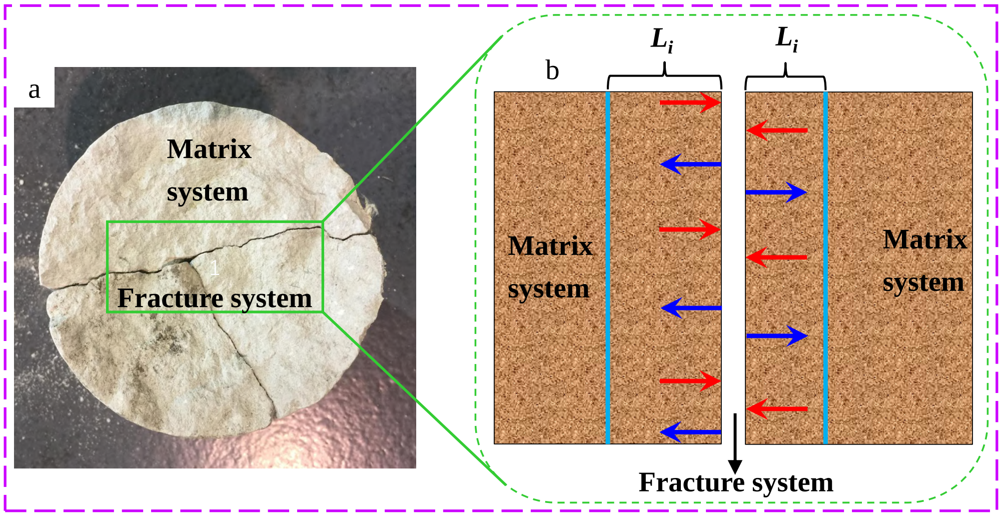


Fig. 1. Schematic diagram of the fracture-controlled matrix unit. Note: The blue arrows represent the direction of water phase flow, and the red arrows represent the direction of oil phase flow (Liu et al., 2020d).

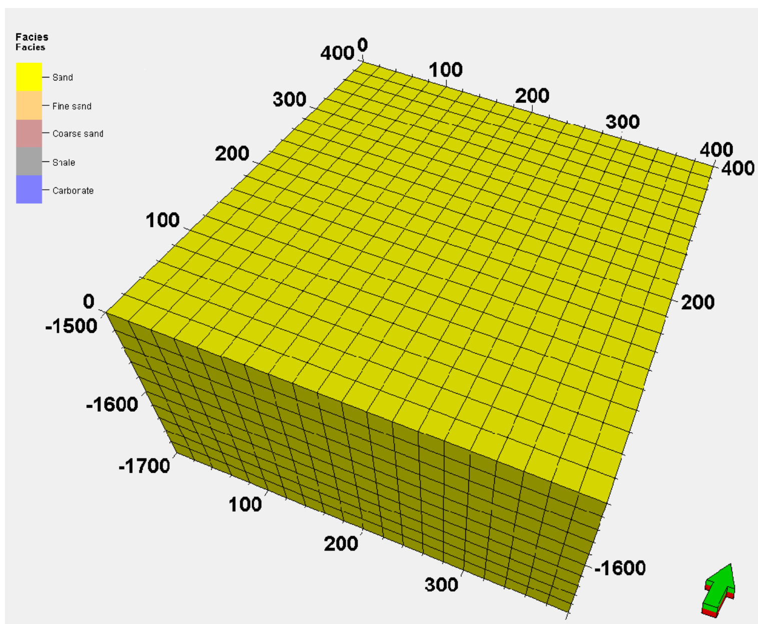


Fig. 2. A reservoir-scale three-dimensional homogeneous sandstone matrix model.

Table 1. Parameters of the sandstone matrix system.

Porosity (%)	Permeability (mD)	Buried depth (m)	Length (m)	Width (m)	Height (m)
10	1	1500	400	400	200

fracture-controlled matrix unit (Fig. 1).

2.2 Matrix model numerical characterization at the reservoir scale

Based on the above, this paper takes sandstone as the research object using geological modeling software (PETREL), and adopts the facies modeling module to establish a reservoir-scale three-dimensional homogeneous sandstone matrix model. The mesh division for the established matrix model is performed, and the mesh size is set as 40×40 cm^2, as shown in Fig. 2. The parameters of the matrix system in the model are shown in Table 1.

2.3 Fracture model numerical characterization at the reservoir scale

The wetting phase (water) mainly exists in the fracture, which communicates with the matrix, and is sucked into the matrix to replace the residual oil. The displaced residual oil

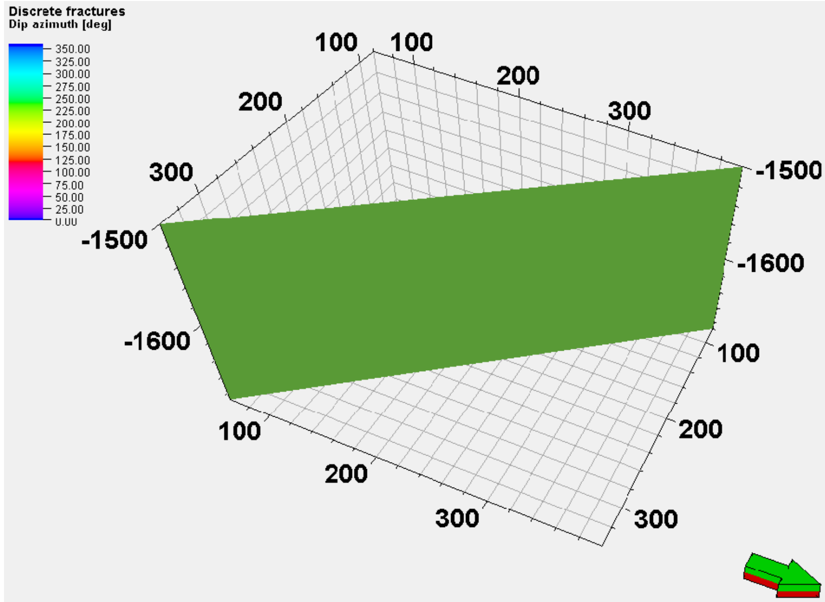


Fig. 3. The DFN model.

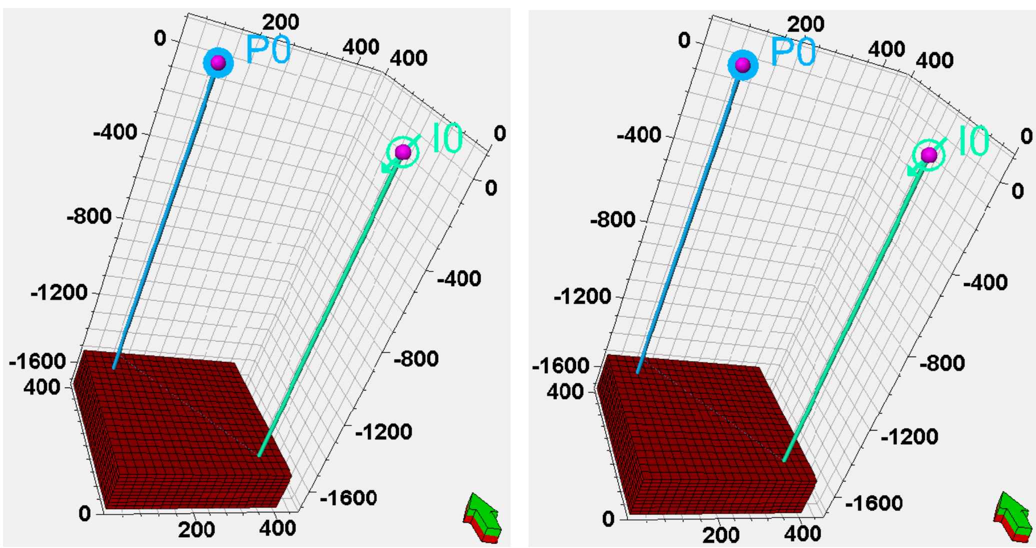


Fig. 4. Numerical model of fracture-controlled matrix element at the reservoir scale.

returns to the fracture, migrates to the production well in the fracture channel, and is finally extracted. Therefore, the fracture system as the hinge of the fracture-controlled matrix unit is of great significance for the process of imbibition oil recovery. In this paper, a single fracture is taken as the research object using geological modeling software and the discrete fracture network (DFN) modeling method to establish a three-dimensional vertical fracture. In this system, the fracture permeability is 1000 mD and the fracture height is 200 m, as shown in Fig. 3.

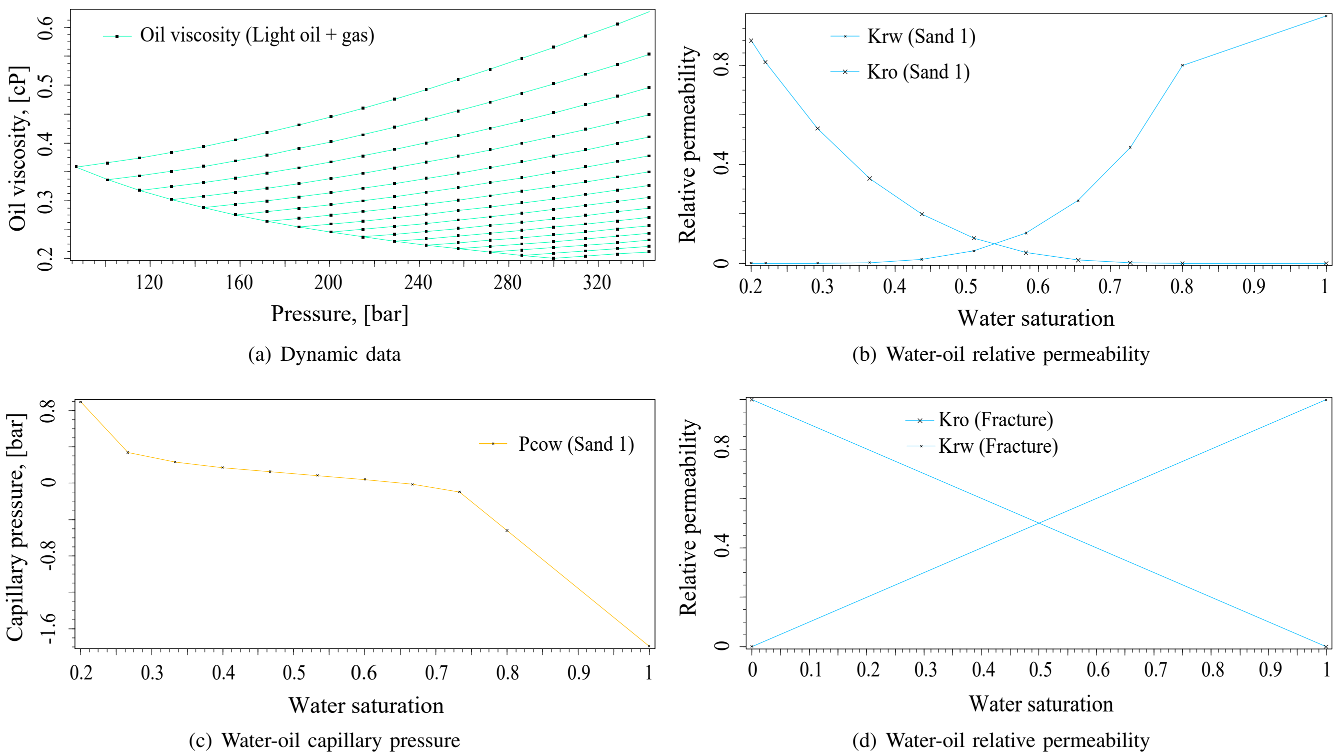
3. Numerical simulation of single fracture-controlled matrix unit

3.1 Model establishment

The fracture model in the previous section is coarsed into the matrix model, and the single fracture-controlled matrix unit numerical model is established. The well distribution mode of one injection and one production is adopted for mining. The coordinates of production wells are (60, 340) and (340, 60), as shown in Fig. 4.

3.2 Fluid properties

Based on the fluid properties, a unified fluid model is established. The formation pressure is 25 MPa and the temperature is 76 °C. According to the different properties of the matrix and the fracture, two sets of different phase permeability models are constructed. In addition, the capillary force is 0.8



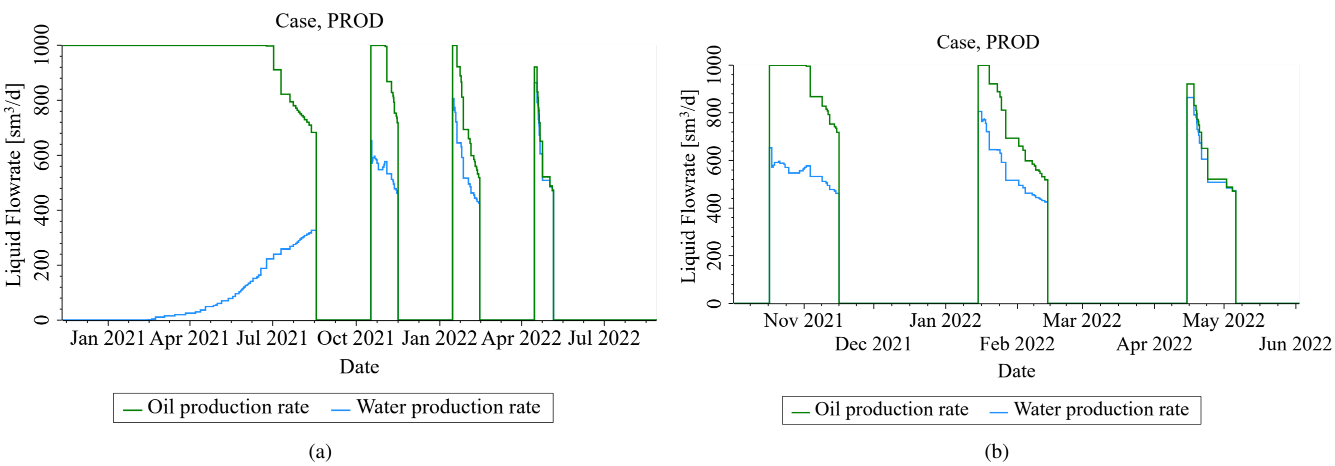
(a) Dynamic data

(b) Water-oil relative permeability

(c) Water-oil capillary pressure

(d) Water-oil relative permeability

Fig. 5. The main fluid model parameters.



(a)

(b)

Fig. 6. Oil and water production curves during huff and puff production in fracture-controlled matrix unit.

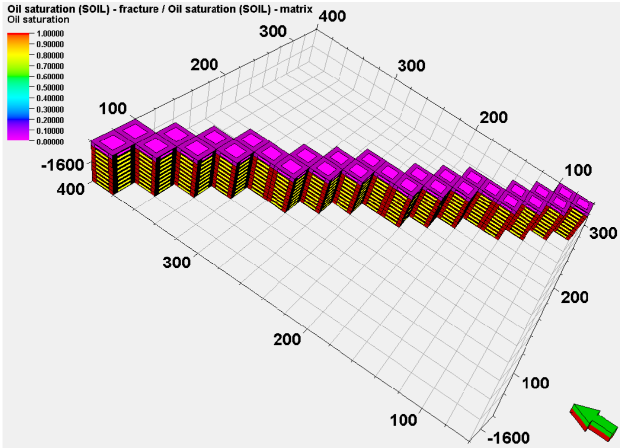
MPa, as shown in Fig. 5.

3.3 Numerical simulation

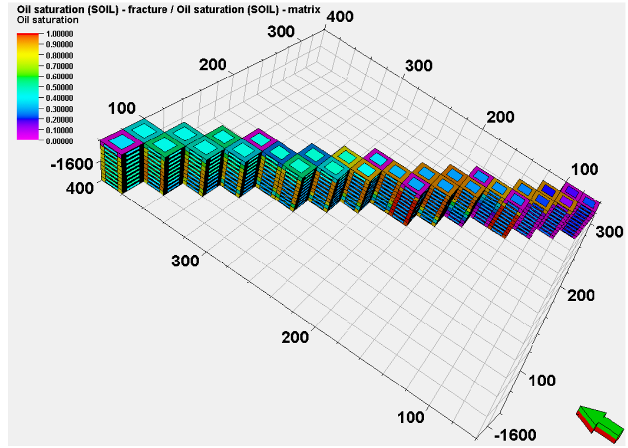
3.3.1 Imbibition oil production

Based on the established single fracture-control matrix unit model, the imbibition numerical simulation is carried out by means of huff and puff production. Firstly, the formation pressure is used for exploitation in the early stage of the process. When the water cut of the production well reaches 80%, the well is shut in. Next, stuffy well operation is carried out for a period of 2 months. Subsequently, the operation is changed to huff and puff production. The production cycle is 2 months stuffy well time, after which the well is opened for one month. The oil production curve of the production well is shown in Fig. 6.

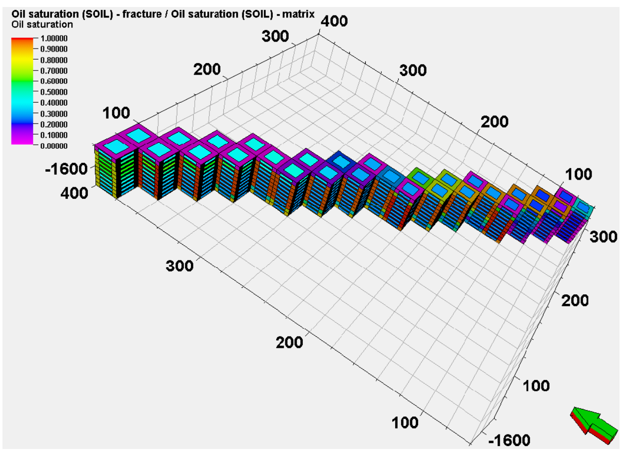
It can be seen from the curve that in the early periods of exploitation, the productivity of the well is very high under the action of formation pressure gradient. As the formation pressure gradually decreases, the productivity of the oil well drops instantly, and the water cut begins to rise. In the middle and late periods of exploitation, the well is shut in, and the water in the fractures is absorbed to replace the oil. When the well is reopened for production, the remaining oil from imbibition is extracted.



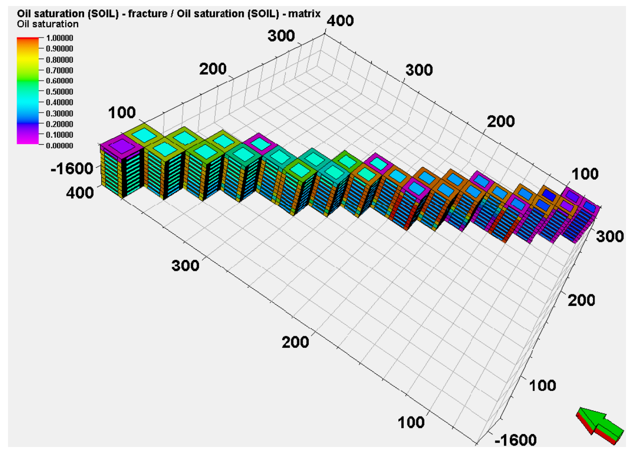
(a) Initial oil saturation in fracture



(b) Oil saturation in fracture before shut-in



(c) Oil saturation when the well is shut in for two



(d) Oil saturation when the well is re-opened

Fig. 7. Three-dimensional oil saturation of fracture with horizontal and vertical length, m.

3.3.2 Fracture oil saturation

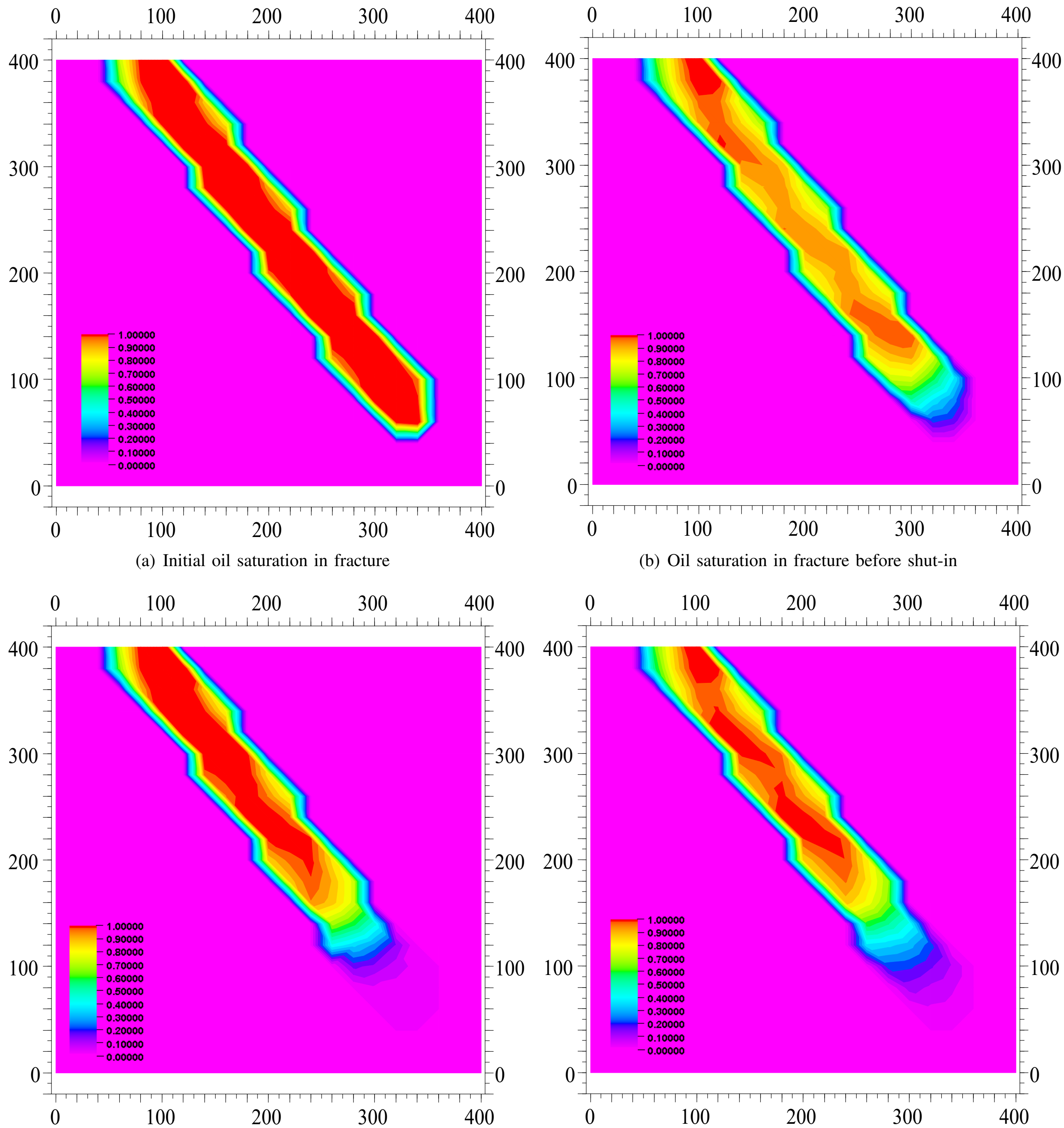
The process of imbibition oil production can be analyzed more clearly and intuitively by studying the oil saturation in the fracture system during the numerical simulation. From Fig. 7, the effect of imbibition oil recovery during the development of oil reservoirs is very obvious. In the initial stage of exploitation, the oil saturation in the fracture is high, but after a period of exploitation, it is significantly reduced. Then, the water in the fracture begins to enter the matrix and replace the oil in it under the action of imbibition. The oil saturation of the fractures has risen, and the imbibition effect is obvious.

Subsequently, the oil saturation is converted to a two-dimensional plane, and a two-dimensional oil saturation image is obtained (Fig. 8). Fig. 8(a) shows that the initial oil saturation of the fracture is 100%. After depletion mining, this value decreases and the water cut increases (Fig. 8(b)), and then the well is shut. In the early stage of shut-in, the wetted phase fluid (water phase) is absorbed into the matrix. The oil phase is replaced, and it enters the fracture (Fig. 8(c)). The oil saturation in the fracture gradually increases after shut-in (Fig. 8(d)). Compared with Figs. 8(c) and 8(d), the longer the shut-in time, the better the imbibition effect. According to the cumulative oil production calculation by software, imbibition can eventually increase the recovery rate by 20%.

4. Conclusions

In this work, the matrix model and fracture model at the reservoir scale of fracture-controlled matrix unit are characterized by the homogeneous matrix model and the discrete DFN modeling method. Finally, the fracture-controlled matrix unit model is established. Under the action of formation pressure gradient, the oil well productivity is relatively high. As the formation pressure gradually decreases, the oil well productivity decreases instantly, and the water cut begins to rise. In the middle and late stage of exploitation, the water in the fracture is absorbed into the matrix to replace the oil. When the well is reopened for production, the remaining oil from imbibition is extracted. Imbibition can eventually increase the recovery rate by 20%.

The results of this work are based on a single fracture model. In subsequent studies, it is necessary to consider the actual situation and upgrade the fracture system of fracture-controlled matrix unit. The single fracture should be transformed to multiple fractures and complex fractures, and multi-



(a) Initial oil saturation in fracture

(b) Oil saturation in fracture before shut-in

(c) Oil saturation in fracture when the well is shut in for one month

(d) Oil saturation in fracture when the well is shut in for two months

Fig. 8. Two-dimensional oil saturation image of the fracture with horizontal and vertical length, m.

parameter simulation should be performed.

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Conflict of interest

The authors declare no competing interest.

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