Energy Proceedings
Vol 56, 2025
ISSN 2004-2965

The Influence of Different Water Quality on Enhanced Oil Recovery by CO_2 in Low Permeability Reservoirs

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ABSTRACT

CO_2 flooding is an effective way to improve recovery factor and achieve CO_2 storage. In the late stage of oilfield waterflooding, due to the long-term erosion of injected water, the geological parameters of the reservoir have changed significantly compared with the initial stage, which has a great impact on the distribution of remaining oil. In the conventional reservoir numerical simulation, the changes of reservoir seepage parameters, physical parameters and fluid-related properties over time are not considered, which leads to the fact that the results of the reservoir numerical model are not conform with the actual oilfield development situation and affect the subsequent CO_2 flooding effect. Aiming at the problem that the effect of CO_2 flooding is not clear after waterflooding in oil reservoir, by using the T-Navigator numerical simulation software, the variation of permeability was characterized by the displacing water multiple. Considering the blockage of suspended solid, oil droplets in different water quality, established a time-varying permeability method for reservoir damage caused by different water quality. Study the influence and reservoir time-varying characteristics of different water quality after waterflooding on enhanced oil recovery by CO_2 flooding. The results indicate that: (1) Different water quality in waterflooding can make an impact on CO_2 flooding. When the core is damaged by poor water quality, the porosity and permeability decreases. (2) After waterflooding, the average recovery factor by CO_2 flooding reduces by 4.54%, the average formation pressure of the injection well increases by 4.56%, the injection capacity declines, the remaining oil saturation rises, and the CO_2 spread range decreases. This conclusion is beneficial to selecting appropriate blocks suitable for CO_2 injection, and provides a reference for the research on enhancing oil recovery by CO_2 flooding after waterflooding in low-permeability reservoirs.

Keywords: CO_2 flooding, reservoir damage, water quality, numerical simulation, displacing water multiple

1. INTRODUCTION

Waterflooding is a common second oil recovery method in oilfields, which can restore and maintain formation pressure, and has extensive water resources, wastewater can be reinjected after treatment. As another way to enhance oil recovery, gas injection development has been applied to many oilfields. Because of its different characteristics from water, CO_2 can reduce the viscosity of crude oil and the interfacial tension, improve the displacement efficiency in the unit pore, and expand the sweep volume.

In the later stage of waterflood development in oilfield, due to the long-term washing of injected water, the macrostructure, microstructure, heterogeneity, fluid composition and fluid distribution of the reservoir have significantly changed compared with the initial stage of development[1], especially the main parameters (porosity, permeability, relative permeability, capillary pressure and crude oil viscosity) that affect seepage[2-3]. These parameters have a great impact on the distribution of remaining oil, resulting in more complex reservoir parameters, seepage characteristics and distribution law of remaining oil. Chen (1999) considered that proceed with waterflood development, particles between pores of medium and high permeability reservoirs would be washed away by water, pore throat would increase, permeability would increase, and reservoir heterogeneity would be enhanced by analyzing the data of two core wells before and after waterflood development[4]. Tang et al. (2009) investigated the

This is a paper for International CCUS Conference 2024 (ICCUS 2024), June 20-22, 2024, Beijing, China.

literature of old oil fields summarized the changes of clay minerals, rock wettability, relative permeability, pore throat radius, formation temperature and reservoir oil viscosity[5]. Wang et al. (2021) pointed out that long-term waterflood erosion would cause complex changes in the micro-pore structure of the reservoir, and the overall pore characteristics would tend to improve. Macropore connectivity improved and the degree of heterogeneity decreased. On the contrary, the micro heterogeneity of the small pores becomes stronger[6].

In conventional reservoir numerical simulation, the changes of seepage parameters, physical property parameters and fluid-related properties are not considered, which causes the running results of reservoir numerical model are not conform with the actual oilfield development. Xu et al. (2015) was in order to accurately study the distribution law of remaining oil in the late stage of ultra-high water cut in integrated oilfield, they proposed a method to establish a dynamic change model by considering the relationship between displacing water multiple and permeability in the calculation process of existing commercial reservoir numerical simulation software[7]. Jiang et al. (2016) aimed at the problem that reservoir physical properties are changed by long-term water washing in the process of oilfield waterflooding, they carried out laboratory experimental research, traditional black-oil model transformation, software compilation and other work, established a quantitative characterization method for the continuous change of physical properties with surface flux, and formed a numerical simulation technology capable of describing the time-varying physical properties of reservoirs[8].

Therefore, based on the core displacement experiment, analyze the influence of seepage parameters and physical parameters on oilfield waterflooding, and establish a time-varying numerical simulation method to analyze the development effect of CO_2 flooding under different reservoir damage degree caused by different water quality.

2. EXPERIMENTAL STUDY ON SEEPAGE TIME VARIATION IN OIL RESERVOIRS

2.1 Experimental Study on the Impact of Different Water Qualities on Development Effectiveness

The experimental conditions: injection pressure is 4 MPa, confining pressure is 15 MPa, temperature is 328.45 K, simulated oil viscosity is 6.7 cp.

The core of the target block was selected as the experimental sample, the basic physical property parameters are shown in Table 1. The water quality information used in the experiment is shown in Table 2.

Table 1 Experimental core foundation physical property.

Core number	Porosity (%)	Permeability (10^{-3} um^2)
X37-1	9.2	0.109

Table 2 Sample water quality information

sampling spot	Water quality type	Suspended solids content (mg/L)	Oil Content (mg/L)	Particle Size (μm)
X block in Ansai Oilfield	Clean water	-	-	-
	Treated produced water	54	36	5.2
	Untreated produced water	8	37	2.2

The experiment steps are as follows :

(1) The core is put into the gripper, vacuumed for 24 hours, pressurized and saturated simulated formation water, then use simulated oil to displace core to establish the saturation of irreducible water.

(2) Use injection water of different water quality for oil flooding, record the oil-water quantity of flow at the exit end, until the exit end no longer produces oil, and the permeability tends to be stable.

(3) Organize the data, clean the core and equipment, and begin to the next set of experiments.

The experimental results are as follows : according to the experimental results, obtained the curves of recovery factor (Fig. 1) and core permeability damage degree (Fig. 2) after oil displacement with different water quality. Under the same injection volume, the recovery factor of clean water is always higher than that of treated produced water, and the former is about 30% higher than the latter. In the process of oil displacement, the permeability damage degree of the treated produced water is always higher than that of the clear water (Fig. 1), indicating that the poor quality of the injected water will affect the injection capacity and the final displacement effect.

Clear water has little damage to the reservoir, and the maximum permeability damage degree is about 37.90%. The treated produced water has moderate damage to the reservoir, and the maximum permeability damage is about 69.35%. Untreated produced water has the greatest damage to the reservoir, and the maximum permeability damage degree is about 81.39% (Fig. 2).

After 100PV injection of clear water, the permeability damage reached 37.9%. The analysis concluded that the core is weak water sensitive. The clean water is low oil content and suspended solids content, but low salinity and a small amount of Mg^{2+}. In this case, the reservoir damage is caused by clay swelling and precipitation blockage.

After 100PV injection of the treated produced water, the permeability damage is about 69%. The water salinity is low, the median size of suspended particles is greater than the main throat. So the reservoir damage is mainly caused by clay swelling and suspended solids blockage. After injection of untreated produced water, the permeability decreased rapidly reached 81.39%. The suspended solids content and oil content are high, the median particle size is large. So the reservoir damage caused by water without treatment is very serious.

2.2 Curve fitting of reservoir damage degree and displacing water multiple

Fig. 2 shows water quality with clear water, treated produced water and untreated produced water respectively represent about 40% reservoir damage, 70% reservoir damage and 85% reservoir damage.

Reservoir damage about 40% (clean water):

$$y = 6E - 9x^4 - 2E - 6x^3 + 0.0002x^2 - 0.0116x + 1.0611$$

Reservoir damage about 70% (treated produced water):

$$y = 1E - 8x^4 - 3E - 6x^3 + 0.0003x^2 - 0.0199x + 0.9959$$

Reservoir damage about 85% (untreated produced water):

$$y = 3E - 8x^4 - 9E - 6x^3 + 0.001x^2 - 0.0511x + 1.2297$$

2.3 Establishment of permeability time-variation method based on reservoir damage caused by different water quality

In the T-Navigator numerical simulation software, the displacing water multiple is defined as the ratio of the total volume of water flowing through the core grid to the pore volume of the core grid. the displacing water multiple is used to characterize the change of permeability. Considering the blockage caused by suspended solids and oil droplets in different water quality, the reservoir permeability showed a downward trend. Using the permeability under different displacement PV measured by water flooding experiments with different water quality, obtained the functional relationship between permeability change multiple and the displacing water multiple. With the increase of displacement PV, the reservoir permeability decreases, the overall relationship is a polynomial function.

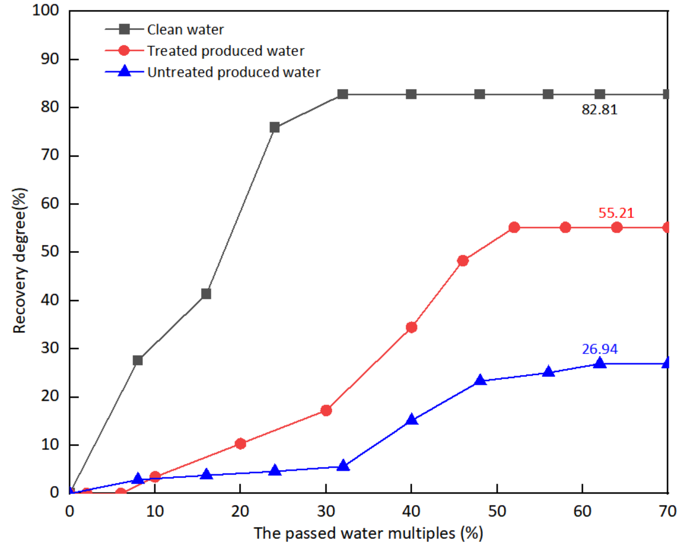


Fig. 1. Comparison of recovery factor degree with different water quality

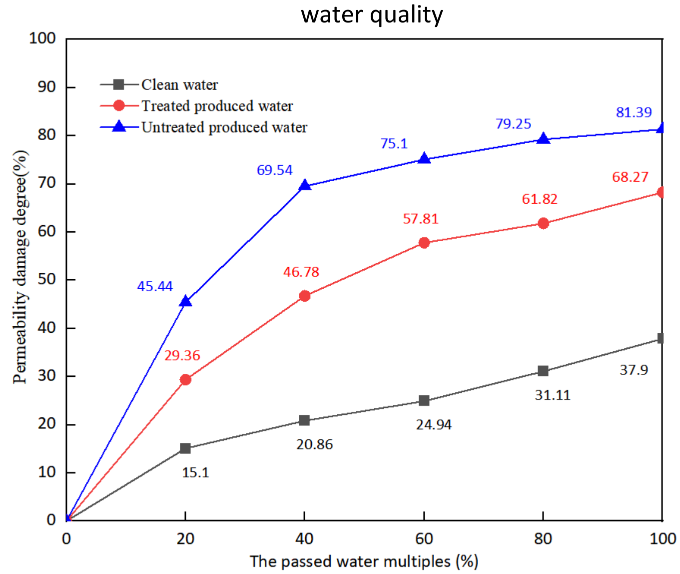


Fig. 2. Damage degree curves of core permeability with different water quality

3 STUDY ON TIME-VARYING NUMERICAL SIMULATION OF RESERVOIR SEEPAGE

3.1 Establish Model and Initialize Properties

Based on the technical specification for numerical simulation application of oil and gas reservoirs (SY/T 6744-2008), the 3D geological model and PVT experimental results, established a numerical simulation model of the Chang 8-1 reservoir in Z3 block using the CMG numerical simulation software (Fig. 3). The simulator chosen the thermal recovery STARS, then used the T-Navigator software to proceed the time-varying simulation.

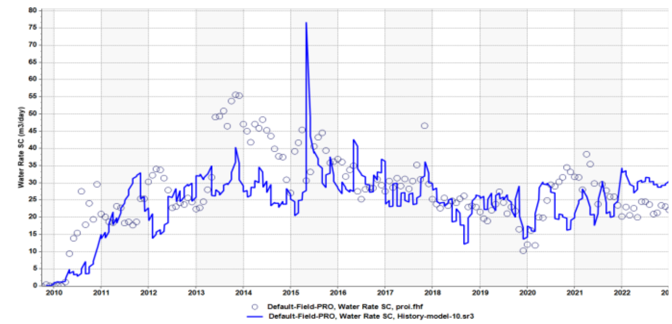
In Z3 Block, the formation pressure is 21 MPa, the reservoir temperature is 359.15 K. The underground crude oil density is 0.7248 g/cm^3, and the viscosity is 1.81 mPa·s. The ground crude oil density is 0.8296 g/cm^3 and the viscosity is 6.77 mPa·s. The original gas-oil ratio is 64.0 m^3/t. Formation water type is $CaCl_2$, total salinity is 85.01 g/L.

Chose the well group Y29-103-Y29-101-Y31-101-Y31-103, based on the existing reservoir physical property data, detailed geological modeling results, tracer tests, and analysis of production dynamic data, analyzed the distribution of the primary fracture system. Determine the secondary fracture system distribution through production history fitting, established a rhombus nine-spot well pattern model for a typical well group.

3.2 Production history fitting

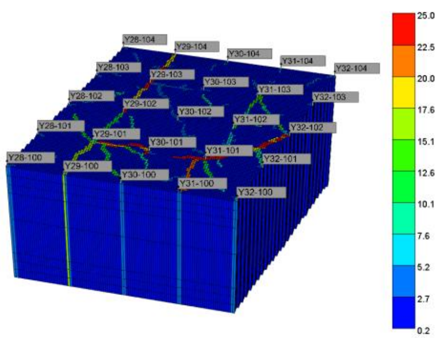
The purpose of production history fitting is obtaining a set of reservoir parameters to dynamically modify the geological static model. Based on reserves fitting, the production history in the Chang8-1 reservoir of Z3 block is fitted to both the entire area and individual wells. The single well is produced at a fixed oil production rate. The fitting indexes included daily liquid production, daily oil production, and daily water production. The historical fitting curve of Y29-103-Y29-101-Y31-101-Y31-103 well group is shown in Fig. 4.

a. Daily oil production.

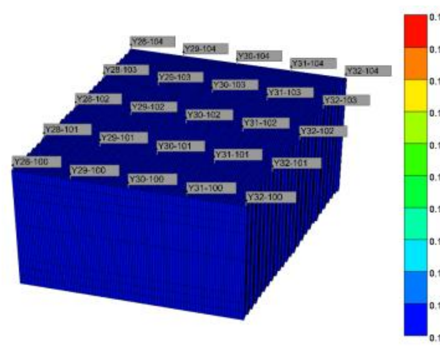


b. Daily water production.

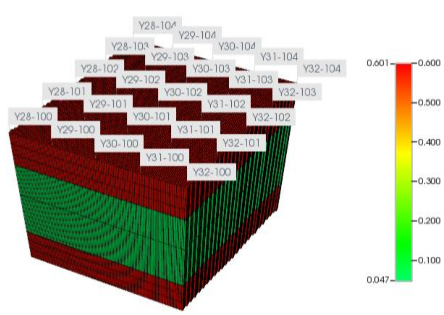
Fig. 4. History fitting curve of Y29-103—Y29-101—Y31-101—Y31-103 well group



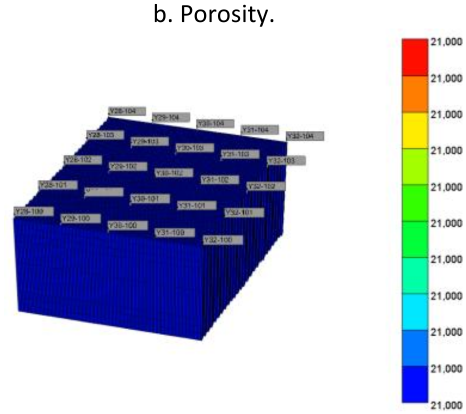
a. Permeability.



b. Porosity.



c. Initial oil saturation.

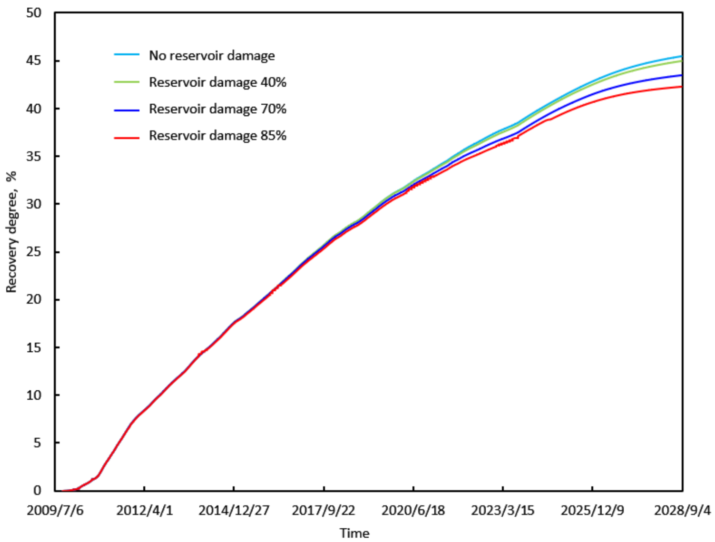


d. Initial formation pressure.

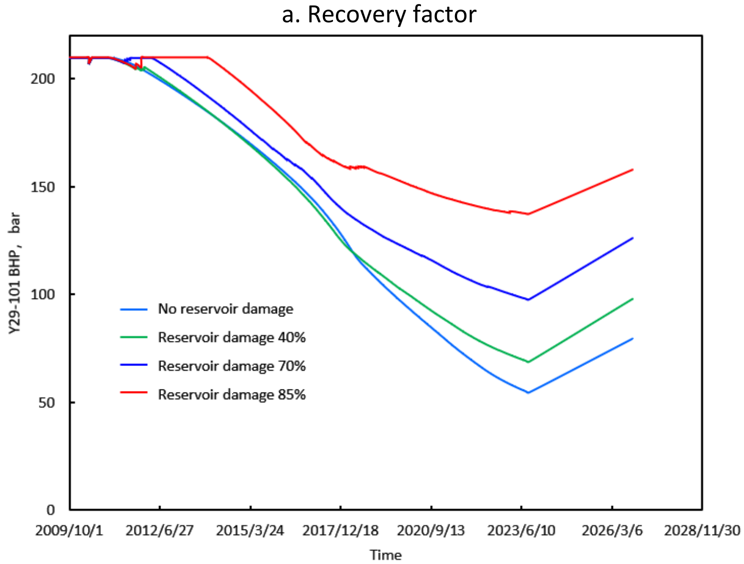
Fig. 3. Reservoir physical properties and initialization parameter fields of Y29-103—Y29-101—Y31-101—Y31-103 well group

3.3 Numerical simulation study on the effect of CO_2 flooding on EOR after water flooding with different water quality

Aimed at the target block, based on the mechanism model of 4 injection 21 production well group considering the distribution of dominant channels. Respectively, set up the CO_2 displacement model without considering the time-varying model and reservoir damage after water flooding, the CO_2 displacement model after clear water flooding considering 40% reservoir damage, the CO_2 displacement model after treated produced water flooding considering 70% reservoir damage, and the CO_2 displacement model after untreated produced water flooding considering 85% reservoir damage. The simulation results are shown in Fig. 5.



a. Recovery factor



b. Bottom hole pressure

Fig. 5. Comparison of recovery factor degree with different water quality

The recovery factor of CO_2 flooding without considering the time-varying model water flooding is 37.52%, the reservoir with greater permeability damage has greater influence on the EOR of CO_2 flooding. Compared with the model without considering reservoir damage, the recovery factor of CO_2 flooding after 40%, 70% and 85% reservoir damage is reduced respectively by 3.42%, 4.23% and 5.96%, average 4.5%. The reduction of formation pressure after CO_2 flooding is respectively 1.07%, 3.92% and 8.70%, average 4.9%.

Compared with the model without considering reservoir damage, the worse the water quality is, the greater the reservoir damage, the smaller the porosity and permeability, the more difficult the formation pressure is to recover, and the lower recovery factor. The injection capacity decreases, the remaining oil saturation increases, and the CO_2 sweep range decreases (Fig. 6 and Fig. 7).

The injected water can not only advance along the dominant channel, but also along the non-dominant channel, the difference is the different forward speed. After displacement by different water quality, the reservoir will be damaged, and impurities such as suspended solids and free oil can cause blockage, resulting in the porosity and permeability of the original dominant channel becoming smaller, and CO_2 will no longer take gas channeling along the dominant channel, but the porosity and permeability of non-dominant channels such as narrow pore throat will be lower, and even form a "dead channel", which is not beneficial to the flow of CO_2. However, displace the remaining oil in small pores needs more start-up pressure, so reservoir damage is not beneficial to CO_2 displacement.

4. CONCLUSIONS

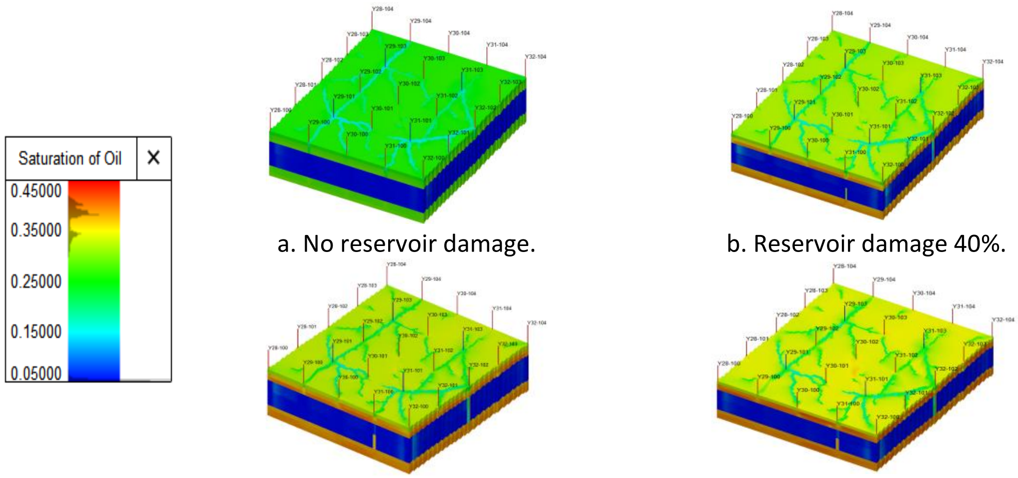
In this study, we used T-Navigator numerical simulation software to characterize the variation of permeability by displacing water multiple. By considering the blockage of suspended solid, oil droplets in different water quality, we established a time-varying permeability method for reservoir damage caused by different water quality, and studied Study the influence and reservoir time-varying characteristics of different water quality after waterflooding on enhanced oil recovery by CO_2 flooding. Based on our comprehensive analysis, the following conclusions can be drawn.

(1) In the displacement experiment of different injected water quality, the water quality deterioration can lead to the reduction of water displacement efficiency, the recovery factor decreases from 82.8% to 55.2%.

(2) Compared with no reservoir damage, the recovery factor of CO_2 flooding considering reservoir damage is reduced by 4.5% average, the bottom hole pressure of injection well is increased by 4.9% average, the injection capacity is decreased, the remaining oil saturation is increased, and the CO_2 sweep efficiency is reduced.

DECLARATION OF INTEREST STATEMENT

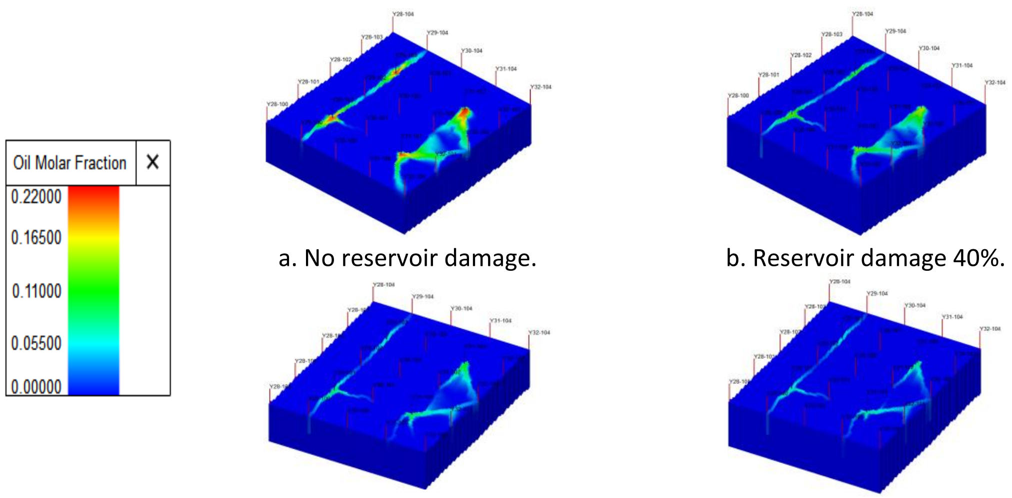
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.



a. No reservoir damage. b. Reservoir damage 40%.

c. Reservoir damage 70%. d. Reservoir damage 85%.

Fig. 6. Oil saturation changes during CO_2 flooding development after water flooding



a. No reservoir damage. b. Reservoir damage 40%.

c. Reservoir damage 70%. d. Reservoir damage 85%.

Fig. 7. CO_2 distribution during CO_2 flooding development after water flooding

(3) Reservoir damage can significantly affect the sweep efficiency of CO_2, resulting in the target reservoir CO_2 storage capacity is less than expected, and the existing natural barrier of CO_2 storage in the reservoir will be destroyed, forming a new leakage path, resulting in ineffective storage. It is recommended to evaluate the reservoir damage degree to ensure the effectiveness and safety of subsequent CO_2 enhanced recovery factor and storage in the late stage of low permeability water drive reservoir.

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