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Optimization and evaluation of CO_2 storage and enhanced oil recovery in low permeability reservoir

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Abstract—In low permeability reservoirs, poor water injection development effect, high water injection pressure, formation energy can not be effectively supplemented and other problems often lead to unsatisfactory development effect, so it is a big problem to change the development mode to improve oil recovery. The injection of carbon dioxide into the reservoir and geological storage of the injected CO_2 can greatly reduce the viscosity of crude oil, improve the fluidity of the oil, and reduce the oil seepage resistance, thus improving the development effect and enhancing the oil recovery. Yesanbo oilfield is located in the south of Dagang oilfield, which is a typical low permeability reservoir. Considering the dual advantages of carbon dioxide geological storage and enhanced oil recovery, this paper chooses this area for reservoir numerical simulation study. Based on the mechanism model, the number of injection Wells, injection velocity, Ratio of vertical to horizontal permeability (Kv/Kh), The influence of critical water saturation value on carbon capture， utilization and storage (CCUS) scheme operation. The results show that a horizontal well with two straight gas injection Wells is the best. The higher the gas injection rate, the greater the carbon storage and cumulative oil production. When Kv/Kh value increases, the carbon storage decreases, and the cumulative oil production increases. Critical water saturation value increases cumulative oil production and carbon storage decreases. The CCUS scheme constructed in Yesanpu oilfield has dual functions of oil displacement and carbon sequestration, which significantly improves oil recovery and deposits a considerable amount of carbon dioxide into the reservoir. This study provides a scientific basis for the operation of CCUS in the oilfield.

Keywords—geological storage of carbon dioxide, enhanced oil recovery, low permeability reservoir

I. INTRODUCTION

With the development of economy, excessive carbon dioxide emissions from the burning of a large number of fossil fuels have brought serious environmental problems and global warming. [1] CCS (Carbon capture and storage) is one of the optimal solutions to reduce carbon emissions under existing technology conditions. [2] CCS has been widely carried out internationally, with 43 large-scale CCS projects being carried out around the world as of 2019. Compared with CCS, CCUS (geological Use and Storage of carbon dioxide) technology can produce economic benefits by "turning carbon dioxide into waste". The technology is expected to achieve zero carbon dioxide emissions from fossil fuel use. [3] Therefore, CCUS technology will become a hot spot for emission reduction application in the following decades, and it is also expected to generate both environmental and economic benefits by using this technology. [4-7]

In the choice of CCUS development scheme, gas-assisted gravity flooding method is used in this paper, which solves the problems of low sweep coefficient and poor oil displacement effect of conventional water injection and water gas alternating injection, and greatly improves oil recovery while burying a considerable amount of carbon dioxide into the reservoir. The principle is to inject gas (CO_2)at the top of the reservoir through a vertical well, and use the gravitational differentiation between oil and injected gas to make the low-density gas flow upward, accumulate at the top of the structure, and gradually push the oil down to the bottom of the production well. The development model is shown in Fig. 1.

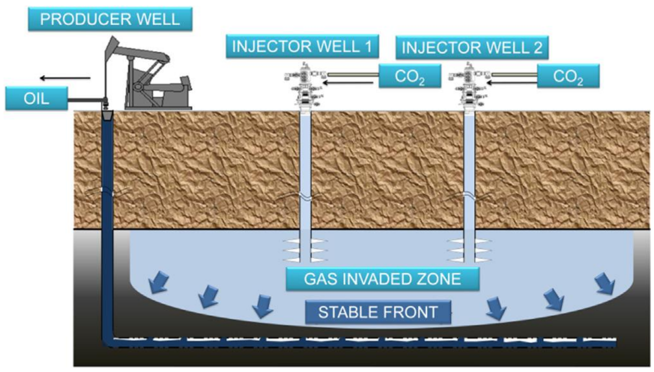

Fig. 1. Develop the pattern diagram[8]

II. RESERVOIR MODELING

In order to improve the development effect of Yesanbo oilfield, enhance oil recovery, effectively develop the remaining oil, and at the same time achieve permanent permanent isolation of CO_2 injected into the reservoir from the atmosphere. Through the following four basic principles:

geological ground combination, design reasonably well location; matching reservoir reserves and determining reasonable well type; optimized and reasonable well spacing; reasonable consideration should be given to both oil production and carbon dioxide geological storage.[9-11] Based on an in-depth understanding of the geological characteristics of Yesanbo oilfield, a 3D model was created using tNavigator software (the software can simulate the CO_2 injection process and take miscible into account). Cartesian coordinate system and single-porosity and single-permeability model are used in this study, and the reservoir parameters are similar to those of Yesanbo Oilfield (TABLE I). TABLE II shows six pseudo-component fluid models. Fig.2 and Fig.3 show oil-water and oil-gas phase permeability curves respectively. The effect of capillary force was not considered in this study. The numerical simulation model of the reservoir is shown in Fig.4. In order to more accurately describe fluid migration around the horizontal well, the well pattern is encrypted around the horizontal well, as shown in Fig. 5.

TABLE I. THE RESERVOIR MODEL

Cartesian reservoir grid (i,j,k)	61×41×10
Grid size (m)	20×20×10
Grid top (m)	3700
Layer thickness (m)	10
Reservoir temperature (℃)	119
Porosity (%)	10
Horizontal permeability (mD)	1.5
Reference depth (m)	3700
Reference pressure (bar)	407
Rock compressibility (1/bar)	0.0003
Net to gross thickness ratios（NTG）	0.5

TABLE II. THE RESERVOIR FLUID MODEL

Pseudo–component	Molar weight	TCRIT （K）	Mol （%）
CO_2	44.01	304.70	0.07
C1、N_2	16.18	163.10	24.89
C2+	50.69	388.68	16.11
C7+	142.52	702.12	26.93
C16+	282.48	792.32	17.59
C27+	602.43	961.09	14.41

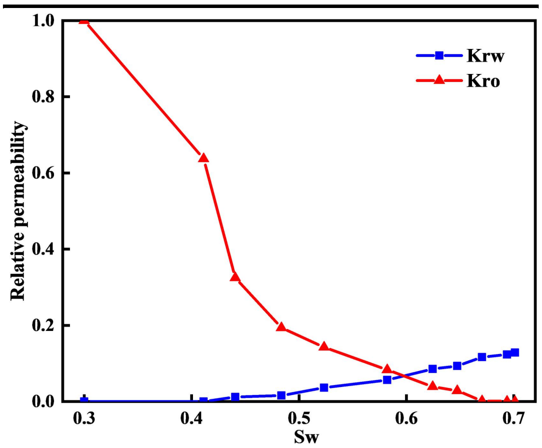

Fig. 2. Oil-water relative permeability curve

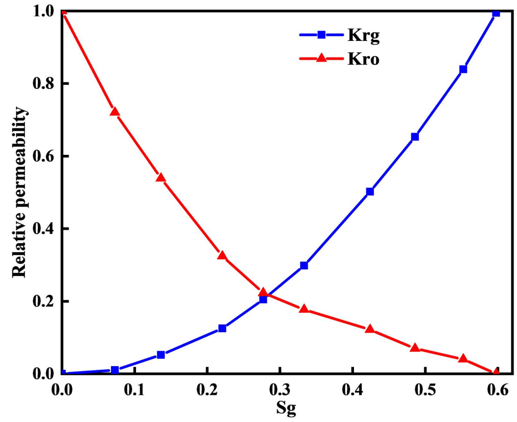

Fig. 3. Oil-gas relative permeability curve

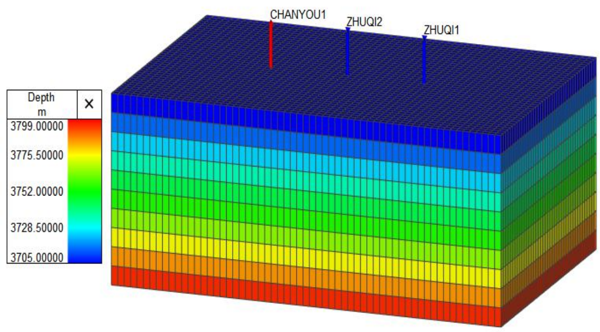

Fig. 4. Reservoir numerical simulation model scheme

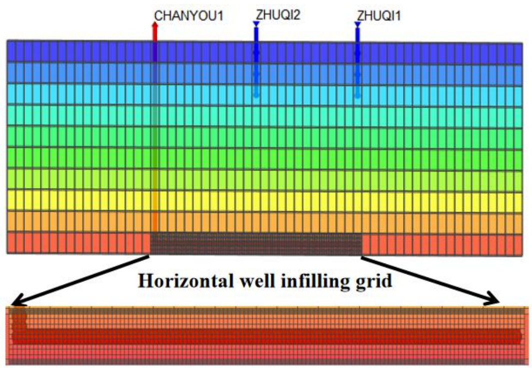

Fig. 5. Well pattern infilling diagram at horizontal well

This paper mainly considers the effects of injection well number and injection well type, CO_2 injection rate, reservoir vertical permeability to horizontal permeability ratio (Kv/Kh) and SWCR on CO_2 geological storage and enhanced oil recovery. The paper also set well control conditions for the production well, with a maximum production gas-oil ratio of $5000sm^3/sm^3$, a maximum water cut of 95%, and a bottomhole pressure of 20MPa. The program runs for 50 years.

III. SCHEME EFFECT ANALYSIS

A. Impact of injection well number and injection well type on CCUS scheme

In the scheme design, this model considers three injection Wells when the production well is a horizontal well, and the gas injection Wells in the three cases are all above the horizontal production well, respectively, one vertical well, two vertical Wells and one horizontal well. Under the same conditions of other parameters, the production rate of CO_2

injection (20,000 sm³/d) was fixed, and the influence of injection well number and injection well type on CO_2 storage and cumulative oil production(Np) was observed. The results are shown in Fig.6-7 and TABLE III.

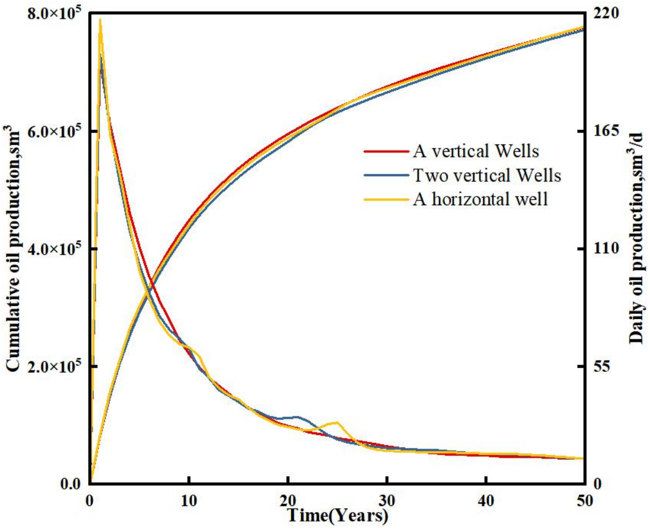

Fig.6. Cumulative oil production and daily oil production curve of three injection schemes

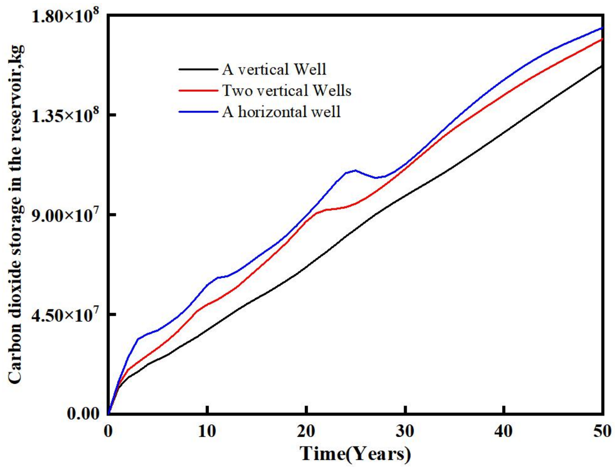

Fig.7. Geologic carbon dioxide storage curves for different injection well types and number of Wells

TABLE III. Running results of the scheme parameters

Injection well type and number	Np/sm³	CO_2 storage/kg
A vertical Well	7.72×10^5	1.57×10^8
Two vertical Wells	7.77×10^5	1.69×10^8
A horizontal well	7.78×10^5	1.74×10^8

It can be seen from Fig.6 that the cumulative oil production curve is basically consistent with the daily oil production curve without significant difference, indicating that different well types and injection wells have no significant influence on the production at the same injection rate.

It can be seen from Fig.7 that different injection well types and the number of injection Wells have an impact on CO_2 storage. It can be seen from the figure that after 50 years of operation of the model, CO_2 storage reaches up to 1.74×10^8kg when the injection well type is horizontal, and 1.69×10^8kg when the injection well is two vertical Wells. When the injection well was a vertical well, the CO_2 storage reached 1.57×10^8kg. Because the horizontal well injected CO_2 more evenly, the production well produced gas slowly, so more CO_2 is buried in the reservoir. However, the cost is much higher than that of the vertical well, and the buried storage only increased by 2.87% after 50 years of model operation, which is not obvious. The CO_2 storage of two vertical injection Wells is 7.1% higher than that of one vertical injection well after 50 years of model operation. Therefore, two gas injection Wells are preferred in this model.

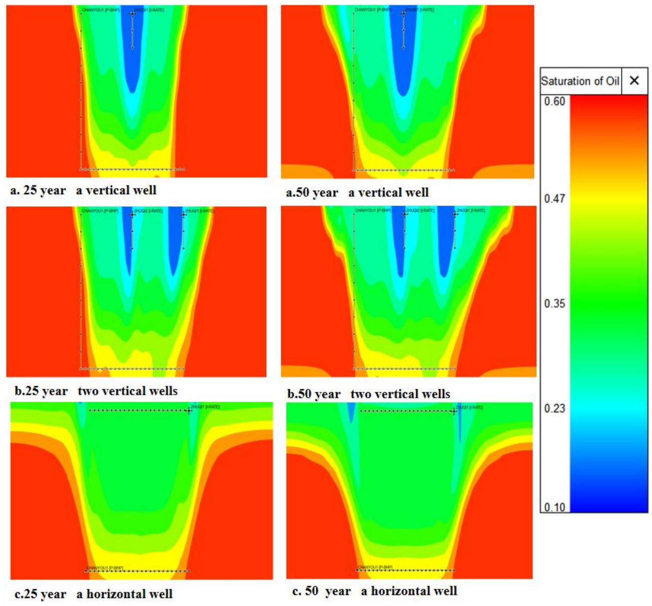

Fig.8.Vertical oil saturation profiles after 25 and 50 years for three injection well scenarios (J =21)（a）A vertical Well（b）Two vertical Wells（c）A horizontal well

The oil saturation profiles of the three gas injection schemes were further analyzed (Fig.8). According to the oil saturation profiles of the three schemes during 25 years of operation of the model, it can be seen that when the gas injection Wells are one or two vertical Wells, the oil saturation around the gas injection well is lower at about 20%. The low value range of oil saturation (blue) is significantly larger than that of two vertical injection Wells when the injection well is one vertical well. When the gas injection well is a production well, the distribution of oil saturation around the well is about 30%. It can be seen that injection gas propulsion in horizontal Wells is more uniform under the same injection volume. Compared with one straight gas injection well, two straight gas injection Wells affect a wider range of gas injection. Although the amount of crude oil produced is basically constant, the carbon dioxide buried in the reservoir is obviously more than that in one straight gas injection well because of the wide range of gas injection.

After 50 years of operation of the model, the injected gas range of the three schemes keeps expanding, and the oil saturation at the edge of the model gradually decreases, and the oil saturation on both sides of the model of the three schemes decreases significantly. The length of the low oil saturation area (blue area) is smaller for two vertical gas injection Wells than for one, indicating that the high gas saturation area is moving more slowly and more injected CO_2 is trapped in the reservoir.

B. *Effect of CO_2 injection rate on CCUS scheme*

The rate of CO_2 injection is one of the most important factors affecting the geological storage of CO_2 and accumulative oil production. When studying the influence of co2 injection rate on CCUS scheme, this paper considers setting six different gas injection rate values for the study (TABLE IV).

Results As shown in Fig.9-11 and TABLE III, the highest cumulative oil production ($77.84 \times 10^4 sm^3$), the highest geological CO_2 storage ($2.43 \times 10^8 kg$) and the highest gas-oil ratio (4636.74) are found at the gas injection rate of $60000 sm^3/d$.

TABLE IV. Running results of the scheme parameters

Case	$i_g(sm^3/d)$	Np/sm^3	CO_2 storage/kg	Gas oil ratio(sm^3/sm^3)
1	1.00×10^4	7.62×10^5	1.35×10^8	5.88×10^2
2	2.00×10^4	7.72×10^5	1.69×10^8	1.44×10^3
3	3.00×10^4	7.76×10^5	1.92×10^8	2.22×10^3
4	4.00×10^4	7.78×10^5	2.12×10^8	2.98×10^3
5	5.00×10^4	7.78×10^5	2.29×10^8	3.83×10^3
6	6.00×10^4	7.78×10^5	2.43×10^8	4.64×10^3

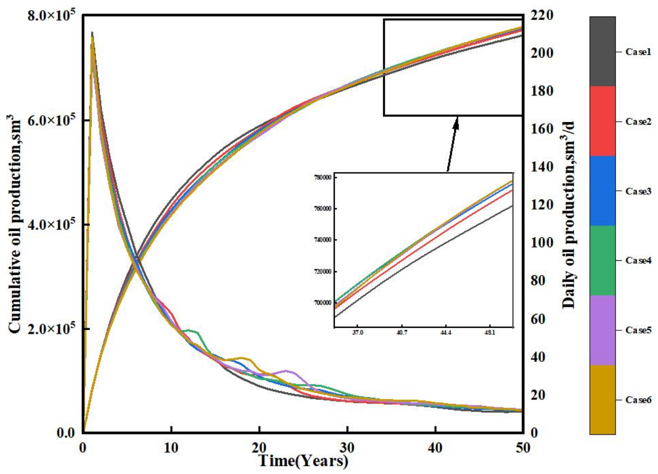

Fig. 9. Cumulative oil production and daily oil production curve of six injection rate schemes

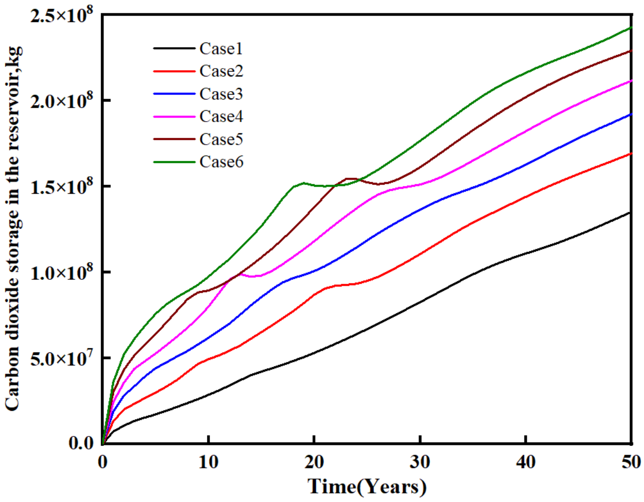

Fig. 10. Carbon dioxide storage curves for six injection rate schemes

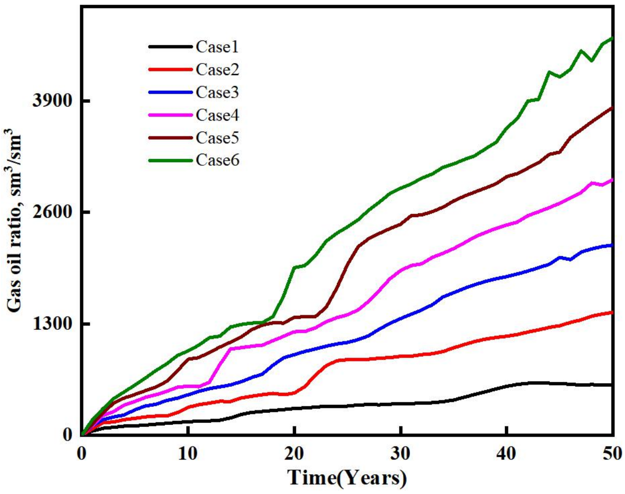

Fig. 11. Gas-oil ratio curves of six injection rate schemes

It can be seen from the six schemes of gas injection speed that, under the condition of constant bottomhole pressure production in horizontal production Wells, gas injection speed has little influence on cumulative oil production, mainly due to the influence of production mode. Under the condition of constant pressure production, too high gas injection speed will cause gas to appear in production Wells too quickly and produce a large amount of gas injection. Fig.11 shows that after 50 years of model operation, the gas-oil ratio of Case 6 is 7.9 times higher than that of Case 1, meaning that there is no reservoir in the reservoir and no reservoir oil is displaced from the reservoir by massive CO_2 injection. Therefore, the injection rate should not be too high to avoid ineffective CO_2 injection cycle.

As can be seen from Fig.10, after 50 years of model operation, the geological CO_2 storage increased with the increase of gas injection, but compared with Case 1, the CO_2 storage increased by $0.34\times10^8 kg$ after 50 years of model operation. It is also observed in the figure that, except for Case 1, the geological CO_2 storage curve flattens or even decreases after 10 to 20 years of operation. This is mainly due to the fact that gas is found in the whole section of the horizontal well and gas production increases, which leads to the flattening and decline of the geological CO_2 storage curve.

C. *The influence of Kh/Kv value on CCUS scheme*

By changing the vertical permeability value of the reservoir in the model and thus changing the Kv/Kh value, the reservoir permeability in the process of CO_2 injection can analyze the geological storage of CO_2 and the degree of crude oil recovery. In this paper, six different Kh/Kv values (0.1, 0.3, 0.5, 0.7, 0.9 and 1.0) were considered for study. Results as shown in Fig.14-15 and TABLE V, when Kv/Kh=1, there is the highest accumulative oil production ($82.86\times10^4 sm^3$) and the lowest geological storage of carbon dioxide ($1.69\times10^8 kg$).

TABLE V. Running results of the scheme parameters

Kv/Kh value	Np/sm^3	CO_2 storage/kg
0.1	7.73×10^5	1.69×10^8
0.3	8.03×10^5	1.56×10^8
0.5	8.14×10^5	1.51×10^8
0.7	8.20×10^5	1.47×10^8
0.9	8.26×10^5	1.45×10^8
1.0	8.29×10^5	1.44×10^8

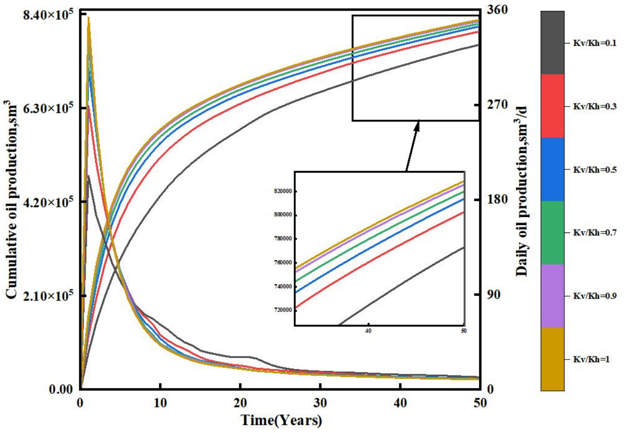

Fig. 12. Curves of cumulative oil production and daily oil production with 6 different Kv/Kh values

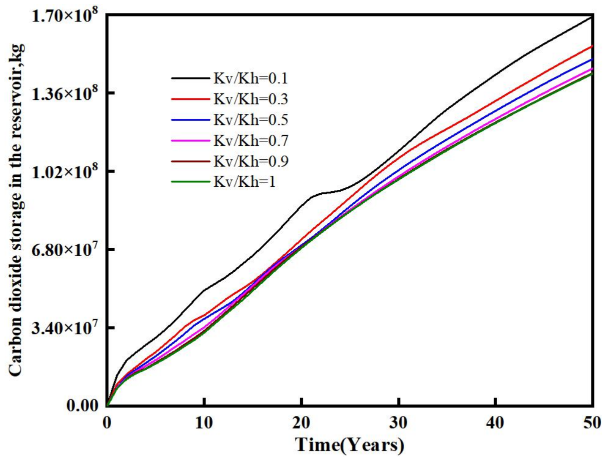

Fig. 13. Carbon dioxide geological storage curves with six different Kv/Kh values

It can be seen from Fig.12-13 that:

(1) Reservoir permeability has a great influence on the degree of crude oil recovery. The higher the permeability, the greater the degree of crude oil recovery under the same production system. The main reason is that the low permeability makes it difficult to inject CO_2 and the pressure wave propagation speed is too slow to play an effective role in displacement, resulting in low cumulative oil production.

(2) When the Kh/Kv value decreases, that is, the vertical permeability of the reservoir decreases, the flow resistance of CO_2 increases, and the breakthrough speed of CO_2 slows down. With the decrease of CO_2 produced by crude oil, the carbon storage increases.

(3)When the Kv/Kh value is low, that is, the vertical permeability is low, the transmission speed of CO_2 in the reservoir is too slow, and the sweep range of CO_2 is small. When the vertical permeability is large, more CO_2 will migrate to the upper direction, and the more it migrates to the upper direction, the larger the swept area and the larger the swept volume will be. In addition, when Kv/Kh is high, CO_2 is more easily recovered from the production well, so the mole fraction of CO_2 is lower than that when Kv/Kh is low. It indicates that high Kv/Kh value will lead to low CO_2 buried in the reservoir.

D. The influence of Critical water Saturation (SWCR) on CCUS schemes

In this study, the critical water saturation (SWCR) varies from 0.2 to 0.42. In this paper, six different critical water saturation (0.2, 0.25, 0.3, 0.35, 0.38, 0.41) are considered to study the influence of SWCR on various parameters of CCUS project. Results as shown in Fig. 14-16 and TABLE VI, when SWCR=0.41, there is the highest accumulative oil production ($77.09\times104sm^3$), the lowest geological buried carbon dioxide (1.69×10^8kg) and the lowest water content (9.18%).

TABLE VI. Running results of the scheme parameters

SWCR value	Np/sm^3	CO_2 storage/kg	moisture content,fraction
0.2	7.48×10^5	1.92×10^8	0.26
0.25	7.48×10^5	1.92×10^8	0.26
0.3	7.64×10^5	1.86×10^8	0.18
0.35	7.60×10^5	1.85×10^8	0.17
0.38	7.60×10^5	1.84×10^8	0.15
0.4	7.73×10^5	1.69×10^8	0.09

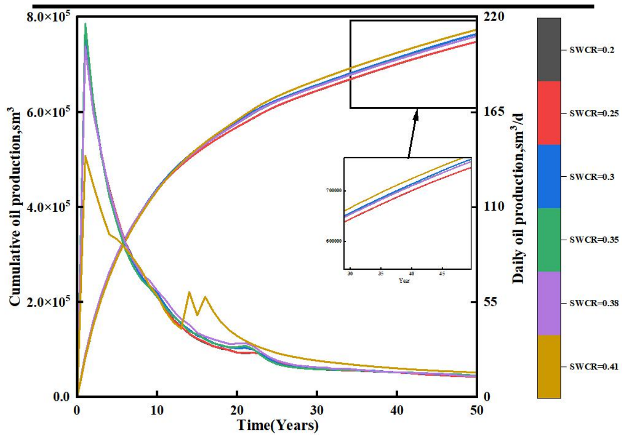

Fig. 14.Daily oil production and cumulative oil production curves of different SWCR values

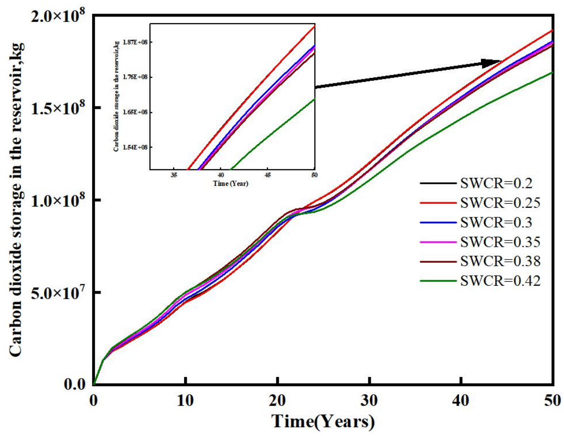

Fig. 15.Geological carbon dioxide storage curves with different SWCR values

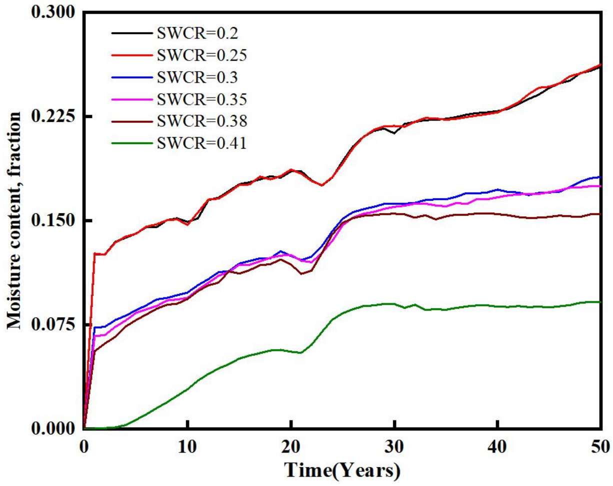

Fig. 16.Moisture content curves of different SWCR values

In the model studied in this paper, horizontal Wells are produced at constant bottomhole pressure, and the water saturation of the model is 40%. Therefore, it can be seen that in the case of SWCR=0.41, the water in the reservoir basically does not flow, and most of it is bound water. In this case, the injected gas will drain a large amount of crude oil into the horizontal production well by gravity. The cumulative oil production of the model is 2.518×10^4sm^3 higher than that of the model in 50 years, but the geological CO_2 storage is 22.81×10^6kg less.

In the case of high SWCR, the geological storage of carbon dioxide is low because most of the water in the reservoir is bound water and cannot flow due to the constant pressure production of oil Wells, so most of the output is crude oil and carbon dioxide injected into the reservoir. In the case of low SWCR, part of the reservoir water can flow into the production well, and part of the injected carbon dioxide occupies the position of the outflow water in the reservoir, resulting in high carbon dioxide geological storage.

It can also be seen from The change of water content in the six schemes in Fig. 16 that when SWCR=0.41, the water content remained below 10% during the 50 years of model operation, and gradually increased in the first 25 years, and basically remained unchanged in the last 25 years. When SWCE=0.2, it reaches 26.1% after 50 years of operation of the model. It can also be seen that when SWCR is low, a large amount of water is produced, which is occupied by CO_2 injection. When the model was running for 20 years, the water content of all six schemes declined to varying degrees, mainly because liquid production remained basically unchanged and water production declined.

Therefore, it can be seen from the six research schemes of this parameter that in the case of constant gas injection in the gas injection well and constant pressure production in the production well, the higher SWCR, the higher the cumulative oil production and the lower the geological storage of carbon dioxide.

IV. Conclusions

Based on the characteristics of strong carbon dioxide gas injection capacity, high oil displacement efficiency and no water sensitivity, the feasibility of constructing CCUS scheme in Yesanbo oilfield is preliminarily discussed. The results show that CCUS scheme is feasible and can achieve good results, which can be further studied.

Different types of gas injection Wells, number of gas injection Wells, gas injection velocity, Kv/Kh value and SWCR value were compared.

In the 50-year prediction of the mechanism model, when the production well is a horizontal well and the gas injection well is a straight well, two straight Wells and one horizontal well, the accumulative oil production is 7.72×10^5sm^3,7.72×10^5sm^3 and 7.72×10^5sm^3 respectively. The geological storage of carbon dioxide is 1.57×10^8kg, 1.69×10^8kg and 1.74×10^8kg respectively.

Considering the economic situation and the difficulty of well construction, it is the best to have two straight gas injection Wells in one horizontal production well. With the increase of gas injection speed, the carbon storage and cumulative oil production increase, but with the increase of gas injection speed, the ratio of gasoline production increases rapidly, but the oil production increases slowly, and the optimal gas injection speed exists. When Kv/Kh value increases, the carbon storage decreases, and the cumulative oil production increases. SWCR increases cumulative oil production and carbon storage decreases.

Compared with the single geological storage of carbon dioxide, geological storage of carbon dioxide and enhanced oil recovery (EOR) scheme take into account two modes of EOR and geological storage of carbon dioxide, which has both economic and environmental benefits.

References

[1] Luo Jinling, Gao Ran, Huang Wenhui, Huo Da, Wang Yanning. Development trend of carbon dioxide reduction and utilization technology in China [J]. Resources and industries, 2011,13(01)

[2] Ren Shaoran, Zhang Li, Sean. CO_2 geological storage: foreign demonstration projects and their enlightenment to China [J]. Journal of China University of Petroleum (Natural Science Edition), 2010,34(01):93-98.

[3] Gu Libing, Li Zhiping, Hou Xiulin. Research progress of geological sequestration of carbon dioxide [J]. geological science and technology information, 2008(04):80-84.

[4] Xu Zhigang, Chen Daizhao, Zeng Rongshu. Progress in geological storage and resource utilization of CO_2 [J]. Advances in Earth Science, 2007(07):698-707.

[5] Hou Zhiwei. Application of intelligent optimization technology in CO_2 geological storage and utilization [J]. Energy and Chemical Industry, 201,42(05):12-18.

[6] Li Shilun, Tang Yong, Hou Chengxi. Present situation and development trend of CO_2 injection EOR technology [J]. Oil and Gas Reservoir Evaluation and Development, 2019,9(03):1-8.DOI: 10.13809.

[7] Gao Jia. Enhanced oil recovery and storage technology of carbon dioxide flooding in reservoirs [J]. China Petroleum & Petrochemical,2017(05):29-30.

[8] Ernesto Vargas Bautista. Capillary, viscous and gravity forces in gas-assisted gravity drainage. Journal of Petroleum Science and Engineering,122 (2014) 754–760.

[9] Yao Xizhi, Research and practice on improving development effect technology of Yesanpu Oilfield. Hebei Province, No.3 Oil Production Plant of Dagang Oilfield, Petrochina,2015-12-02.

[10] Ban Yanhua, Zhang Zhuxin, Qin Yiyan, Wang Yajing. Countermeasures and potential analysis of undeveloped reserves in Yesanbo area, southern Dagang [J]. science and technology of west china, 2014,13(02):1+16.

[11] Liu Enying. Study on the distribution law of remaining oil in low-amplitude reservoirs in Yesanbo Oilfield [J]. china petroleum and chemical standard and quality, 2021,41(07):124-125.